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ESA CONTRACT No **AO/1-4469/03/NL/SFe**	SUBJECT **BIONICS & SPACE SYSTEMS DESIGN TECHNICAL NOTE 3**		CONTRACTOR **UNIVERSITY OF SURREY**
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ABSTRACT:
This document is Technical Note 3 for the Bionics & Space Systems Design study. Its topic – the application of biomimetics technology to space exploration – builds on Technical Note 1 survey of biomimetics. It was conducted by the University of Surrey with the support of the University of Sussex, University of Bath, EADS Astrium, and the Open University. It focuses on selecting specific biomimetic technologies that have near-term application to space exploration. In particular, we focus on those aspects of space exploration related to planetary exploration. Such planetary exploration missions will become more challenging as missions focus on astrobiological investigation which represents a complex set of challenging task requirements. Many of these technologies will have wider applicability across space missions.

The work described in this report was done under ESA contract. Responsibility for the contents resides in the author or organisation that prepared it.

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BIONICS & SPACE SYSTEMS DESIGN

AO/1-4469/03/NL/SFe

Technical Note 3

Space Applications of Biomimetics

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LIST OF APPLICABLE DOCUMENTS

[AD1]	Invitation to Tender	IMT-CTM//SFe/2003.960
[AD2]	Bionics & Space System Design: Statement of Work (Appendix 1)	GSP-03/L27
[AD3]	Draft contract (Appendix 2)	AO/1-4469/03/NL/SFe
[AD4]	Special Conditions of Tender (Appendix 3)	AO/1-4469/03/NL/SFe
[AD5]	General Conditions of Tender for ESA Contracts	ESA/C/290 rev 5
[AD6]	Biomimicry – A Review	ESA pdf publication (Mark Ayre)
[AD7]	Bionics & Space Systems Design Technical Note 1 (Survey of Biomimetic Technologies)	Alex Ellery et al, University of Surrey publication
[AD8]	Bionics & Space Systems Design Technical Note 2 (Space System Design Challenges for Biomimetic Research)	Mark Ayre, ESA publication

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LIST OF ACRONYMS, ABBREVIATIONS AND TERMINOLOGY

ACT	Advanced Concepts Team
AI	artificial intelligence
AO	announcement of opportunity
AOCS	attitude and orbit control system
BAS	British Antarctic Survey
CBNT	Centre for Biomimetic & Natural Technologies
CCNR	Centre for Computational Neuroscience & Robotics
CDH	command and data handling
CDR	critical design review
EPFL	Ecole Polytechnique Federale Lausanne
ESTEC	European Space Research & Technology Centre
FDR	final design review
GOFAI	good old-fashioned AI
ITT	invitation to tender
MTR	mid-term review
OBDH	onboard data handling
PDR	preliminary design review
PI	principal investigator
PM	project manager
PRR	preliminary requirements review
PSSRI	Planetary and Space Science Research Institute, Open University
SMP	study management plan
SoW	statement of work
SSC	Surrey Space Centre
SSR	system requirements review
SSTL	Surrey Satellite Technology, Ltd
TBC	to be confirmed (by the Agency)
TBD	to be determined (by the contractor)
TBS	to be specified (by the Agency)
TN	technical note

TT&C	tracking telemetry and command
WP	work package
WS	work shop

TABLE OF CONTENTS

0. Executive Summary

In this document, we present selected biomimetics technology that may have near-term application for space missions in general, and robotic exploration missions in particular. It further builds on TN1 in indicating where some generic biomimetic technologies may have applicability in space missions, and like TN1, the emphasis is on control systems by virtue of its integrative function with any system. The structure of the document begins with a general introduction to biomimetics and why biomimeticvs has much to offer space exploration technology in the context of the requirements for high degrees of autonomy in future space missions. We then introduce microtechnology which although a traditional technology provides a context for introducing biomimetic approaches which also emphasise small dimensions, low power, low mass and high efficiencies. We then suggest that the traditional approach to spacecraft engineering might be replaced with a mechatronic approach to systems design which is integrative so lending it to a biomimetic approach. However, despite this recommendation, we have followed the traditional spacecraft subsystem breakdown in the following chapters. First, in considering "onboard propulsion", we consider the various forms of biological locomotion, primarily for robotic explorers for planetary environments. Second, we consider bio-inspired onboard power systems, particularly microbial fuel cells. We only briefly consider biological approaches to thermal control. In considering onboard computer systems, we highlight two important biomimetic concept. Genetic programs offer much promise for space application by exploiting evolution to generate high level programs which are analysable using software engineering methods. Furthermore, we present the possibility of employing neural networks in VLSI hardware format to gain high speed pattern recognition computation rather than reliance on software. We consider onboard control systems which we view as the central theme of biomimetics and also of the spacecraft by virtue of its integrative function. In particular, we consider the application of biomimetic techniques to space systems such as symbol-based artificial intelligence methods and behaviour control and look further to the future to the potential for genetically-evolved neural network controllers. In consideration of onboard communications and electronic systems, we suggest that the use of FPGAs offer the potential for the implementation of evolved hardware systems in both rf and non-rf electronic devices. We consider the ground system interface to the spacecraft, initially examining traditional VR techniques and current speech recognition systems, and look further to the future at the potential for direct neural-electronic interfacing exemplified by cochlear implant technology. We consider structural and mechanical aspects of spacecraft by considering smart materials and the use of biomimetic artificial muscle actuators to replace traditional electric motors. However, in particular, we consider the issue of compliance in biological systems in overcoming limitations in control systems to provide the basis for interaction with the real world. This emphasises a general principle that mechanical structure cannot be divorced from control. We consider payloads are primarily sensors – indeed, biological vision is considered in detail, particularly active vision which has immediate application to electriomagnetic radiation sensor payloads; tactile sensing and hair-based transduction are considered as essential for physical environment interaction; olfaction is considered as a chemical sensing modality that has applications in planetary exploration. We also consider sensor fusion as a biological capability that would enhance autonomous data gathering. In considering spacecraft system reliability, we examine several bio-inspired methods to ehancing reliability – multi-agent coordination and immunological approaches to fault tolerance. Finally we briefly consider the human element to spaceflight, particularly the notion of closed ecological life support systems and the use of microbial methods. Finally, we conclude by suggesting that we have merely considered a tiny fraction of biomimetic techniques that may be exploited for space missions. To support the document, we have included appendices which provide tutorials in artificial intelligence, neural networks, genetic algorithms, the architecture of the human brain, and space medicine.

1. Introduction

Biomimicry[1] involves "reverse engineering" of the principles of evolutionary design of biological organisms in order to implement biological solutions to general engineering problems. The problems encountered by biological systems are in many respects similar to those encountered in engineered systems. Biological evolution has evolved robust solutions to many problems encountered in the environment through the most stringent of tests – survival (or more properly, inclusive reproductive fitness which may be approximately correlated with survival). In robotics, the commonest model for such biological inspiration is the insect. Biomimicry applied to space engineering promises the prospect of high miniaturisation, high integration and packaging efficiency, high energy efficiency, and high autonomy and robustness. We suggest that the primary *raison d'etre* for adapting biological solutions to the design of spacecraft and space missions is to enhance autonomy, i.e. relieve the ground-based (for robotic spaceflight) or spacecraft-based (for human spaceflight) human personnel from interacting with the space mission. This implies the need for extensive adaptability, robustness and reliability.

There is little doubt that biological systems are hugely successful in solving problems encountered in their environments. There is thus much that engineers can learn from biology to emulate in their design of engineering systems – this is biomimicry (or biomimetics, or bionics, or bio-inspiration). The success of biological organisms is attributed to the process of natural selection whose primary metric is such success – failure implies extinction. No wonder engineers have begun to examine biological systems to learn how organisms solve problems. It seems appropriate therefore to examine biological solutions to common biological and engineering problems. Biological evolution has had a vast amount of time in which to determine function features within organisms that confer survival value – 550 million years of multicellular evolution have generated some 5-10 million species, of which some 1.7 million have been catalogued. This represents a huge database of biologically-inspired solutions to problems. Invertebrates represent the "simplest" creatures as their neural structures involve at least an order of magnitude fewer neurons than in vertebrate systems. Invertebrate joints are generally mechanically simpler than vertebrate joints. The simplest have ~10^3 neuron structures yet are capable of complex behaviours, highly sensitive and sophisticated sensory processing and limited forms of association.

The reverse engineering of biological organisms has recently become a significant research effort to solve engineering problems by learning from biological solutions to similar problems imposed by the natural environment. Such reverse engineering of biology has met with varying degrees of success for a number of reasons, but renewed impetus has emerged following technological developments and increased scientific understanding. Such biological solutions offer insights into alternative strategies for designing engineering systems. Biological systems represent millions of years (billions of years in the case of microbes) of trial-and-error learning through natural selection according to the most stringent of metrics – survival. This project seeks to attempt to assess the current state-of-the-art in biomimicry and to apply this knowledge to the next generation of space systems. In this application, there is a curious mis-match in that biomimicry seeks to learn from organisms that evolved in environments on Earth, while space systems operate in a variety of hostile, non-terrestrial environments. However, by exploiting the robustness of biological

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[1] Biomimicry is to be distinguished from species (Batesian) mimicry in which one species of animal impersonates another unpalatable or dangerous species. This strategy is particularly common in prey species to predatory birds. It is particularly common in insects, eg. the harmless African grasshopper resembles a stinging ant.

organisms and the wide variety of environmental conditions in which they can survive, this mismatch should not present a difficulty. It is important however to ensure that we distinguish between functional aspects of biological evolution (which contribute to functionality) and incidental aspects (which do not). This is often difficult to do in complex systems as relationships and functionality are not necessarily well-defined – this problem may be illustrated by the question of whether consciousness is a necessary condition for intelligent behaviour, or is merely an incidental artefact resultant from the convoluted evolutionary history of the human brain. However, in many cases, abstraction of the central properties of biological systems which impart a given functionality is readily achieved. Evolution by natural selection does not provide optimal solutions to environmental problems but generates "satisficing" solutions due to the historical constraints of available genetic resources and the general requirement that an organism exists on the minimum amount of energy. However, although optimal solutions are characteristic of engineering, biological systems exhibit high robustness and adaptability to environmental variables implying a higher degree of redundancy in overall design. Certainly, the test for biological evolution is survival through functional effectiveness – the most stringent test within the hostile natural world.

There are a number of major differences between engineered products and biological systems [Plotnick & Baumiller 2000]:

1. Organisms are characterised by cylindrical shapes and curved surfaces while engineered structures are characterised by straight edges and sharp corners
2. Engineered products atre generally constructed from homogeneous materials while biological materials are composite at a variety of scales
3. Metallic materials are absent in organisms
4. The wheel and axle are absent from nature
5. Engineered structure are designed for stiffness (and so tend to be brittle) while organisms favour strength over stiffness for toughness
6. Biological features often have multi-functional roles

1.1. SPACE MISSION AUTONOMY

Robustness and adaptability is particularly critical in space exploration as the environments to be explored are typically unknown with unknown dynamics and variability. In particular, as space exploration missions demand greater sophistication and functionality, so the requirements for miniaturisation, autonomy, robustness, and survivability become paramount. According to Mjolsness & Tavormina (2000): "…how biological systems store and retrieve information, control development, fabricate structural components, build molecular machines, sense the external environment, reproduce and disperse themselves throughout the environment, engage in error detection, and carry out self-repair can pay big dividends to space exploration." This is particularly the case as space exploration missions give way from global reconnaissance to more focussed *in-situ* investigation requiring enhanced capabilities. The current and logical exploration strategy adopted by space agencies follows a similar plan:

(i) global reconnaissance by orbiters
(ii) in-situ exploration of targeted sites
(iii) multiple in-situ exploration of multiple targeted sites
(iv) robotic return of extraterrestrial samples to Earth for detailed analysis
(v) human missions to provide detailed wide-area exploration

A critical issue for space systems is that of autonomy – the distances involved, particularly once spacecraft venture beyond Earth orbit, preclude real-time control, necessitating high degrees of onboard autonomy. Indeed, although such missions are typically associated with exploration spacecraft, the issue of autonomy is also relevant to the Earth orbiting fleet, as ground station control is the dominant factor in operational costs. The greater the autonomy of a spacecraft, the greater its self-reliance as they operate at increasing distances from Earth deeper into outer space. The essential characteristic of an autonomous agent (a system with a particular function) is the capacity to allocate resources to perform its functional role and maintain its viability (Steels 1995). To be able to do this requires the ability to repair themselves and/or adapt to the environment. Such autonomy includes, but is distinct from, the property of automaticity – automatic systems are self-regulating in that they follow steering laws, but autonomous systems are self-governing in that they develop their steering laws. They must do this continuously by sensing, and acting upon its environment. This requirement imposes a consequent degree of loss of control but this loss of control is only partial – the relinquishing of only those aspects of control that ensure the survival and function of the spacecraft in response to uncertainty. The autonomous spacecraft is essentially a robot designed for function in outer space or within the influence of hostile planetary environments. However, engineered robots are highly deficient in comparison with the simplest organisms with regard to their sensory robustness, pattern recognition capabilities, adaptability to variability in the environment, and actuation flexibility. Biological systems on the other hand exhibit autonomy *par excellence*. They evolve, adapt and learn in a variable environment whilst maintaining their functionality. Even evolutionarily-primitive creatures such as insects exhibit high degrees of adaptive and flexible behaviour despite being endowed with limited neural tissue, a characteristic probably related to their skeletal design. Space systems more than many other engineering applications place emphasis on these qualities – a uniquely symbiotic relationship: as space systems demand more capabilities from biomimicry engineering, so biomimetic science will advance.

We are concerned with the application of biological solutions to the problem of spacecraft missions for exploration (and other space missions). Specifically, we are interested in replicating the capabilities of biological organisms in robotic spacecraft. Norman (1980) defined an animate system as one that has goals and purposes, maintains and protects itself (survival), regulates its own operation (homeostasis) and reproduces itself. Although biological life is characterised by self-replication as one of its basic properties, we exclude this aspect from further consideration due to its limited application to spacecraft of the near future. Fritz et al (1989) suggested that the primary goal of an intelligent system is survival and self-preservation (though more properly self-replication), and this is the guideline we use in applying biological lessons to the engineering of spacecraft. There are certain aspects that we exclude from this proposal as they are too immature technologically or of limited direct application to spacecraft design:

(i) Human hibernation and related closed loop life support systems as these relate to long-term technologies with applications limited to human spaceflight; furthermore, the skills mix of the proposal consortium has been built to contribute to the main issues of biomimicry rather than human and animal physiology.

(ii) Human-machine interfaces such as those being developed via neural-silicon interfaces are omitted as having limited applicability for space exploration missions as well as low maturity. This form of neural-silicon interfacing may be a long-term capability leading to “cyborgs” but is considered too long term for further consideration (and associated ethical issues).

(iii) Communication as exhibited in the animal kingdom has limited applicability to space communications and most lessons are currently incorporated (e.g. pulse code modulation and frequency modulation in animal signals rather than amplitude modulation); human communication through language is complex in structure (with syntactic, semantic and pragmatic aspects) and is not readily abstracted into applicable form beyond ready-existing programming languages based on syllogistic logic.

(iv) Generic artificial life, genetic networks and self-replication studies as these are undeveloped in terms of technological application (e.g. von Neumann's kinematic self-replicator).

(v) Nanotechnology including carbon nanotubes, RNA processing, etc are under-developed for technological application in the near future and would require considerable effort for treatment to do the subject equivalent justice.

(vi) Techniques of generic rather than specific biological origin, e.g. in-situ resource utilisation, which might be regarded as a form of "feeding".

We highlight five main broad biological principles that are particularly relevant to space systems:

1. The principle of autonomous behaviour to minimise reliance on ground systems
2. The principle of integration of mechanics, control, software and electronic systems
3. The principle of robustness for survival under widely variable conditions
4. The principle of compliant, multi-functional structures as part of a control system
5. The principle of neurally-inspired control systems with selectionism (e.g. neural Darwinism)

The emphasis of this document is in control aspects as this provides the linking thread between all aspects of a spacecraft, particularly autonomous spacecraft. Of particular relevance is Sanchez et al's (1997) taxonomy which represents how evolutionary processes occur in organisms, behaviours and species – the POE (Phylogeny-Ontogeny-Epigenesis) model. Phylogeny is concerned with biological evolution by natural selection through generations of a population and speciation. Ontogeny refers to embryonic development of multicellular organisms during cellular differentiation. Epigenesis is associated with an organism's ability to adjust its behaviour due to changes in its environment, ie. learning during the organism's lifetime. Although there appear to be significant differences, there are many similarities.

1.2. CAVEATS TO BIOMIMETIC SPACE SYSTEMS

We believe that biomimicry has much to offer space systems design and the future of space missions. The planetary application aspect of space missions fits well with the role of biological organisms – the need to survive and function effectively in a variable, hostile and uncertain environment. Indeed, we submit that space applications provide a unique driver as a user application to biomimetic research in such a way that current piecemeal approaches to biomimicry will give way to structured and well-defined research programmes. There are however, a number of important provisos:

- Biological solutions are not globally optimal, being dependent on evolutionary history and heritage, so application of bio-inspired solutions must be selective. An organism cannot be optimally evolved for all roles, tasks, and situations. Specialisation typically involves compromises elsewhere.
- Biological organisms have evolved within a terrestrial environment rather than in space or other planets (though biological solutions may be sufficiently robust to accommodate the different physical and chemical properties encountered in space exploration)

- Biological evolution does not carve up the world into mechanical, structural, electrical, software control modules, rather that all aspects of biological solutions co-evolve together

Furthermore, there appears to be a nonlinear relationship between biomechanical structure and function – evolution cannot develop perfectly designed solutions to problems. Hence, the biomimicry employed for space systems is more properly bio-inspired rather than replicated wholesale from the biological organism. There are numerous examples of differences in approach to solving the same problems, e.g. fixed wing aircraft that separates lift from propulsion compared to flapping wings of flying animals that provide both lift and propulsion. However, given recent advances in materials and computing, bio-inspired solutions have become more amenable to emulation in engineered systems. Unlike conventional engineering approaches, biological solutions are integrative involving simultaneous co-evolution of mechanical structures with control systems to provide their functionality. The appropriate level of abstraction of such bio-inspiration is not a trivial issue, e.g. artificial neural networks (ANN) used for control systems are highly simplified and re-structured abstractions of biological neural architectures (neurons are typically represented as RC network-based processors) [Barto et al 1983]. It is not currently clear if such ANNs abstract sufficient properties from their biological analogues to replicate their function fully – biological neural networks exhibit complex dynamics including strange attractors characteristic of chaotic systems. Some aspects of such abstraction are enforced, e.g. abstraction of material properties in biomimetic materials. The chief motivation for pursuing biomimicry is that it promises a degree of miniaturisation, high integration and packaging efficiency, high-energy efficiency, and high autonomy and robustness. As the robotic exploration of the solar system proceeds, so surveys will give way to more detailed and more challenging scientific investigation necessitating implementation of these characteristics. Similar characteristics will be required for robotic systems that support human missions. Such robotic systems will relieve astronauts from "cable repairman" tasks to those strategic tasks more suited to the human brain leading to greater cost-effectiveness of human deployment in space [Ellery 2002].

There are two major problems with the application of reverse engineering biological systems to spacecraft, both related to the notion that terrestrial biological systems have evolved in a terrestrial environment so the biological solutions may not have direct applicability:

1. The survivability of materials under space or planetary conditions - it is unlikely that many of the materials considered here (particularly those associated with biomimetic capabilities) are qualified for space operation. This will entail a programme of space qualification which we consider lies outside the scope of this study.
2. The problem of terrestrial robotic control research applied to planetary surfaces of rugged, rocky terrain – most research in mobile robotics has been based within artificial, indoor environments. Indeed, one of the commonest behaviours adopted in behaviour-based robotics is wall-following – walls do not exist on other planets! A related issue concerns vision processing, which is dominated by the extraction of straight-lines from images in order to delineate objects. Straight-lines however are not found in natural environments (though curiously, the mammalian visual cortex possesses neurons sensitive to straight-line orientations [Linsker 1986a,b]).

1.3. APPLICATION OF BIOMIMETICS TO SPACE SYSTEMS

This document builds on Technical Note 1 which provides a survey of biomimetics technology and Technical Note 2 which maps biomimetics technologies to the ESA space technology master plan (based on Dossier 0). In fact, this Technical Note 3 includes some additional material that was not covered in TN1. The ESA technology tree has three levels of increasing detail, but we consider only the coarsest level here. The technology domains essentially correspond to spacecraft subsystems:

- On-board data systems (includes artificial intelligence, behaviour control, learning, genetic-neural approaches and distributed intelligence)
- Space systems software (includes artificial intelligence, behaviour control, learning, and genetic-neural approaches)
- Spacecraft power systems (includes photosynthesis and microbial fuel cells)
- Space system control (includes artificial intelligence, behavior control, learning, distributed intelligence and genetic-neural approaches)
- Radiofrequency/electromagnetic payload systems (includes distributed intelligence and deployment mechanisms)
- Mission control and operations (includes artificial intelligence, behaviour control, learning and distributed intelligence)
- Flight dynamics and navigation (includes distributed intelligence and behaviour control)
- Ground station system and networking (includes artificial intelligence and distributed intelligence)
- Automation, teleoperation and robotics (includes all aspects of biomimetics)
- Life/physical science payload instrumentation (includes biomimetic sensing, learning and artificial intelligence)
- Mechanisms and tribology (includes actuators, deployment mechanisms, structural control and biomimetic sensors)
- Optics and opto-electronic systems (includes biomimetic vision)
- Propulsion (includes biomimetuc structures, deployment mechanisms, actuators and biomimetic materials)
- Structures and pyrotechnics (includes deployment mechanisms, biomimetic structures, biomimetic structures and sensors/actuators)
- Thermal control systems (includes biomimetic materials, bio-thermal control)
- Environmental control life support systems and in-situ resource utilisation (includes artificial intelligence, behaviour control, learning, distributed intelligence, biomimetuc sensors)
- Space components (includes microsystems and evolutionary hardware)
- Materials and processes (includes biomimetic materials)

In addition, the service/application areas of space systems include:

- Earth observation (includes biomimetic sensors, artificial intelligence, learning and genetic-neural approaches)
- Telecommunications (includes biomimetic structures and materials, artificial intelligence and behaviour control)
- Navigation (same as telecommunications)
- Science and exploration (includes all aspects of biomimetics)

- Manned spaceflight and Life/Physical science (includes all aspects of biomimetics)
- Long-tern applications (includes all aspects of biomimetics)
- Space transportation (includes biomimetic sensors, artificial intelligence and behaviour control)
- Select key areas (includes autonomy and deployment mechanisms)

Given the considerable overlap in biomimetics technologies and their application, we consider that the mapping between space technologies and biomimetics applications requires a coarser approach. It is worthy of note that there are a number of technology/service areas which require consideration of all aspects of biomimetics – automation and robotics, science and exploration, and human spaceflight and life/physical science. A natural approach would then be to concentrate on robotic explorers to provide a comprehensive coverage of biomimetics applied to space missions. This is in part our approach here. However, in order to ensure realisation of applicability beyond such missions, we have adopted consideration of generic spacecraft systems. Our concern is to bear in mind the application of biomimetic technology to space missions generally. Our perceived mapping takes the current form, which reflects in part the structure proposed in this document (though not all aspects are covered):

Table 1.1 – Biological Analogues to Spacecraft Subsystems Matrix

Spacecraft Subsystem	**Relevant Biological System**
Space systems engineering	Evolution, embryonic development and cognitive psychology applied to modularity
Human element	Human-machine interfacing, closed loop ecology and hibernation strategies
Space environment	~~UV protection and oxidant tolerance~~
Propulsion system	Animal locomotion
Attitude control system	Animal navigation and vestibular system
Power system	Photosynthesis, ATP energy storage ~~and in-situ resource utilisation (food)~~
Thermal control system	~~Thermoregulation, psychrophilic and hyperthermophilic extremophile strategies~~
Command and data system	Animal ethology, biological neural nets, central pattern generators, learning and behaviour control
Communications system	Animal communication and human language
Structural system	Biomimetic materials and structures
Payloads (sensors)	Special senses, active vision, optic flow, electronic noses and tactile sensing
Reliability	Autonomy, self-repair, immune system

A spacecraft is coupled to a hostile and highly variable physical world. The importance of physical bodies for intelligent robotics has been traditionally denied explicitly in the Good Old Fashioned Artificial Intelligence (GOFAI) approach. However, cognition is not abstract symbol manipulation and cannot be divorced from bodily constraints imposed by interaction with the real world – the biological world explicitly declares this as natural selection is imposed on organisms by their interaction with the physical world. This requirement for interaction with the real world is also imposed on engineering structures that must adapt to their surroundings such as robotic spacecraft.

This interaction with the real world is the key to biological evolution – evolution effectively incorporates aspects of the environment into the structure and behaviour of the organism which enhance survival (or more properly, inclusive reproductive fitness). This is how organisms are "designed" by natural selection. The artificial carving of the physical world into electronics, mechanics, structures and control systems, as is traditional in engineering, is one which is not adopted in biological evolution. A biological organism is an integrated machine including active sensory input, dextrous mechanical output and a complex integrated control system. The issue of control and that of structural compliance are tightly correlated and cannot be treated separately. Part of this capability is a direct product of the compliance of the organism's mechanical structure. The evolution of animal control systems occurs in parallel with body morphological evolution – they have co-evolved. Thus, biological control is one part of the functional component of biological structure.

Pfeifer (1996) suggested that there were a number of general design principles for situated autonomous agents (fungus-eaters), which are required to survive robustly in real-world environments:

1. fungus eaters principle – the situated agents must be complete systems with the properties of autonomy without human intervention, self-sufficient to sustain themselves over extended periods of time, embodied within a physical system, and situated within the environment with which it interacts.
2. ecological niche principle – the agent must be designed for a particular environmental niche.
3. parallel, loosely coupled processes principle – as exemplified by Braitenburg architectures, complex behaviours emerge from a large number of asynchronous independent processes without central control.
4. value principle – the agent must be embedded in a value system that is based on self-learning rather than pre-programmed categories.
5. sensory-motor coordination principle – sensory-motor coordination of the agent is dependent on its interaction with the environment, eg. movement often generates correlations in sensory patterns as the basis of grounded concept formation and object representation.
6. ecological balance principle – there must be a match between the complexity of the agent's sensors, control architecture, actuation capability, and its ecological niche.
7. cheap design principle – good designs are cheap in that they exploit the physics of interaction with the real world niche environment to minimise information processing requirements.

The application of biological evolution and development to systems design offers useful lessons in the application of modularity to spacecraft design. Traditional satellite design involves developing each subsystem seperately and iteratively from scratch. This is expensive but modular designs based on heritage through multi-purpose platforms (similar to evolutionary heritage) are inefficient. The human element (as part of a human mission or with less relevance the ground control station) may be influenced by the development of ecological principles to life support systems, direct neural-electronic interfacing and hibernation strategies. This aspect is probably more long-term technology than the other biological technologies considered so we exclude this from this project. The space environment itself imposes requirements on the design of a spacecraft – this includes the thermal environment, radiation environment and oxygen erosion. Biological strategies for protection against ultraviolet radiation and peroxide protection in biological cells may be applicable. The biological analogue for propulsion systems is animal locomotion such as legged locomotion, flight, swimming and burrowing. The attitude control system biological analogue is animal navigation and vestibular sensing. Most spacecraft power systems are based on solar arrays which have obvious similarities to biological photosynthesis. Power storage on spacecraft is typically accomplished by batteries or fuel cells of which the biological analogue is ATP energy storage in the biological cell. A related aspect to biological energy generation is feeding which is a form of in-situ resource utilisation (ISRU)[2]. The biological analogue of thermal control is thermoregulation and unicellular extremophile survival strategies of psychrophiles and hyperthermophiles. Spacecraft command and data handling may be correlated with animal ethology, biological neural nets, central pattern generators, reinforcement learning and behaviour control. The spacecraft communication system has biological analogues in animal communication (such as alarm calls) and human languages – we exclude this from this study due to its limited prospects for new generic applications beyond computer languages and natural language understanding (such as SmarterChild which has its roots in the famous ELIZA program). Biomimetic materials and structures with multi-functional capabilities are the biological analogues of the structural subsystem of a spacecraft. Spacecraft payloads are typically sensors or scientific instrumentation. The biological analogues to this are the special senses including active vision (the integrated vestibular-ocular reflex), smell (which functions similarly to the gas chromatography mass spectrometer), tactile sensing, etc. An important aspect of spacecraft design is reliability associated with fault tolerance which has biological analogues in immunity, self-repair and autonomy. The most important aspect of biological systems – reproduction – is omitted from this study (though it has space application in the von Neumann probe concept but this represents a long-term technology).

Biological organisms overcome many of the limitations of current state-of-the-art robotic exploration systems in several areas:

- Increased mobility: access and safety
- Efficient sensor processing and interpretation
- Compliant and dexterous manipulation
- Efficient communication/coordination strategies
- Computationally-efficient decision-making

Mimicry of biological systems can be achieved by using small, mechanical platforms, which can be built at low cost, instrumented and used as platforms for carrying scientific instruments. These systems are often called "Biomorphic or Biomimetic Explorers", and NASA JPL has already carried out the preliminary BEES (Bio-inspired Engineering of Exploration Systems) studies (see fig 2.1, 2.2 and 2.3) [Thakoor 2000]. These biomorphic explorers will be used for exploration of sites difficult to reach by traditional platforms. The aim of biomimetic explorers is to display certain functional aspects of biological systems to gain advantage over standard mechanical designs, such as mobile robotic systems. The exploration of poorly understood planets and moons, or the surveillance of hazardous environments is a difficult challenge, where the versatility to deal and

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[2] Although we have not covered this aspect here, recent discussions between Dr Alex Ellery of the Surrey Space Centre, University of Surrey and Prof Charles Cockell of the Planetary & Space Sciences Research Institute, Open University have yielded a potential research programme to examine the possibility of replicating biological chemolithoautrophy whereby energy production may be obtained from Fe minerals without high temperatures using enzymes which could potentially be of high utility for planetary missions.

quickly adapt with unkown or unpredictable situations and environmental conditions could be critical. In particular, biomimetic systems will be small, lightweight, low-cost and low-power systems. Such devices can offer robust and economical colonies of intelligent robots for wide area exploration of planets. However, an important consideration for such miniaturised systems is that their surface area-to-volume ratio increases – this has two important consequences: their power dissipation increases requiring greater power volume density, and their structural strength increases allowing greater loads. Each robot would be capable of pattern recognition, autonomous learning, and self-repair. BEES places special emphasis on locomotion mechanisms – surface-roving, burrowing, hopping, hovering, flying with reconfigurability – by adopting direct-driven limbs without complex chassis. Active sensor fusion may be implemented through insect-based optic flow may be combined with mammalian vestibular-ocular reflexes based on neural models. Multiple small fliers in particular could be deployed from an altitude of 12-15 km above the Martian surface to explore the Valleris Marineris canyon within an entry probe of mass ≤ 10 kg, eg. sycamore seedwings. Such approaches offer reliability through redundancy, decreased mission duration through parallelism, and decreased cost due to economies of scale and reduced mass.

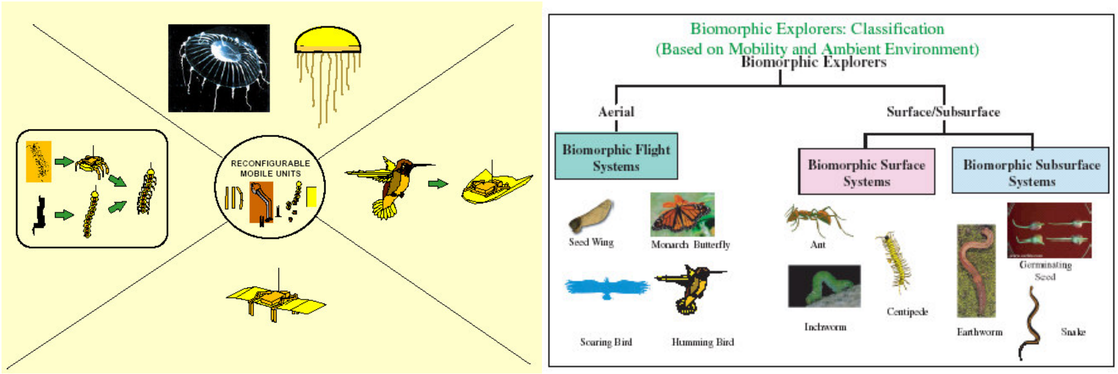


Fig 1.1 (a) Varied mobility modes of Biomimetic explorers (Sarita Thakoor, NASA JPL); (b) Examples of biological inspiration in different mobility categories (Sarita Thakoor, NASA JPL)

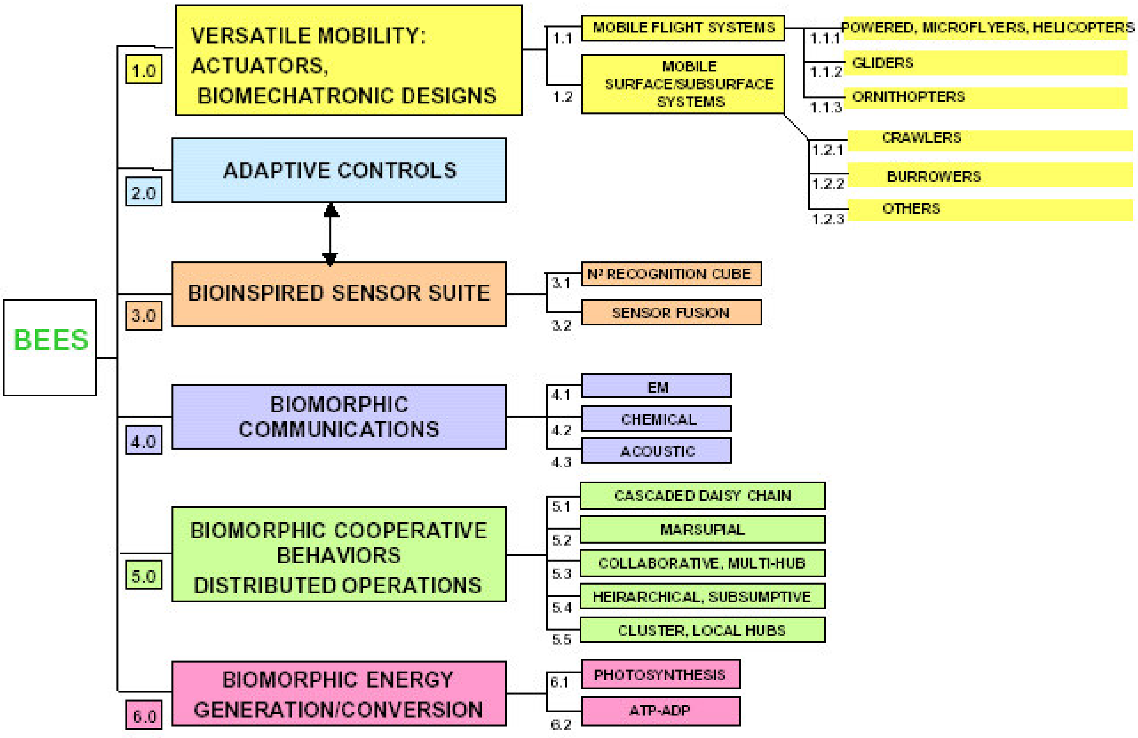


Fig 1.2 NASA's Bioinspired engineering of exploration systems (BEES) subsystems breakdown (Sarita Thakoor, NASA JPL)

In some mission scenarios, biomimetic explorers could complement the abilities of the larger and relatively expensive exploration platforms (e.g. landers, rovers, and aerobots). They may possess varied mobility modes: surface-roving, burrowing, hopping, hovering, flying or swimming, to accomplish surface, subsurface, atmospheric and oceanic exploration. In some cases, they may be envisaged as being preprogrammed for a specific function, and could serve as "no-uplink, one-way communicating" beacons, spread over the exploration site, autonomously looking for/at the object of interest. Co-ordinated/co-operative exploration scenarios are conceivable, for example, in a hierarchical organization, these biomimetic explorers would report to the next level of exploration mode (say, a large conventional rover) in the vicinity. This would allow high spatial access and affordable exploration with a substantial amount of scouting for information about new, currently non-accessable areas at lower cost and risk, combining a fast running rover to cover long distances and deploying numerous biomimetic explorers for in-situ sensing and local sample analysis/acquisition. Some examples of robotic explorations missions that we might consider for biomimetic applications include: a Mars rover, Europa lander, Titan aerobot, comet sample return, asteroid sample return as candidate missions focussed on astrobiology.

2. Microtechnology as a Biomimetic Context

Miniaturisation is essential for space missions to decrease launch costs and shorten development and production times. Micro and nano-technologies (MNT's) allow the creation of functional devices with extremely small dimensions; up to less than one-hundredth of the width of a human hair for nano-technologies. Micro Technologies or MEMS (Micro Electro Mechanical Systems) are usually fabricated using standard silicon-chip processing, offering immense and diverse capabilities in very small packages. The incorporation of MNT's into spacecraft design has a number of benefits including possible reduction in mass, low power consumption, low volume, high reliability and low cost and it is anticipated that these technologies will form an integral part of space biomimicry.

This section is split into four parts. Part 1 discusses in general what microtechnology is and why it is useful. Part 2 discusses microtechnology for space, whilst Part 3 discusses the application of microsystems in space. Part 4 discusses spacecraft concepts, with microsystems. Finally Part 5 discusses microtechnology in space biomimcry.

2.1. INTRODUCTION TO MICROTECHNOLOGY

2.1.1. Definitions and Terminology

"Micro Technology" is the name for all devices using parts within 1mm and 1μm, whilst "Nanotechnology" is used to describe many types of research where the characteristic dimensions are less than about 1,000 nanometers.

There are different definitions for Microsystems used in Europe, the USA and Japan and consequently there is often confusion about what actually qualifies as micro technology

In Europe a microsystem (i.e. MST or Microtechnology) is defined as

"…an intelligent miniaturised system comprising sensing, processing and/or actuating functions. These would normally combine two or more of the following: electrical, mechanical, optical, chemical, biological, magnetic or other properties, integrated onto a single or multichip hybrid"

(Microsystems in the 4th Framework IT, Sept. 1996).

In the USA, Microelectromechanical systems, or MEMS, are integrated micro devices or systems combining electrical and mechanical components, fabricated using integrated circuit (IC) compatible batch-processing techniques and varied in size from micrometers to millimetres. These systems merge computation with sensing and actuation to change the way we perceive and control the physical world (MCNC, 1996).

In Japan, Micromachines are composed of functional elements only a few millimetres in size which are capable of performing complex microscopic tasks. (Micromachine Centre 1996). We should be as flexible as possible using the Japanese definition in a broad sense and possibly the EU definition for MST. The USA description of MEMS is possibly too restrictive as it implies only silicon IC technology.

The distinction between micro systems and micro electronics is blurred. There is often confusion whether electronics which incorporate large scale integration (eg ASIC's) and advanced packaging methods (MCMs) can be described as MST in their own right. The answer is probably no as it is not generally recognised that electronic devices (e.g. processors) are examples of MST. However, in order to benefit from the reductions achieved with MST devices, the supporting electronics will inevitably employ advanced designs. In addition, a goal of MST is to integrate devices and electronics, possible due to the similar materials and manufacturing methods employed. Therefore, devices and electronics will tend to become one and the same but at this stage of development we must remember there is a difference. This overlap is best illustrated by the following Figure 2-1.

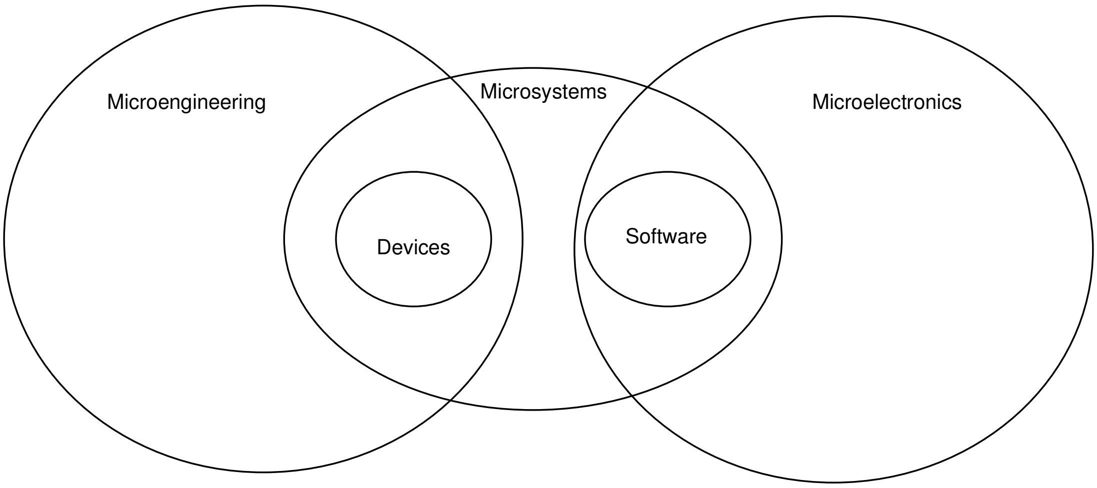


Figure 2-1 Microengineering / Microelectronics Commonality

2.1.2. What is MST and where is it used?

Microsystems Technology (MST) is based upon techniques established by the semiconductor industry to manufacture the modern integrated circuit. The integrated circuit, particularly in the form of the silicon chip, is the basis of entire industries such as computers, telecommunications and video games. The development of application specific integrated microsystems may well create a similar industry by the early part of the next century.

Microsystems technology can combine electronics, mechanics and optics at significantly reduced dimensions to achieve high performance and high complexity in a very small volume, e.g. a few cubic millimetres, with correspondingly low power consumption and weight. MST enables unique products to be made, which would be either too expensive or impossible to manufacture with conventional macro-engineering techniques. For example, MST drug delivery systems are being developed which will be small enough to be implanted into the human body and contain sensors, control valves, an intelligent computer chip and a power source. Such systems will deliver minute controlled amounts of a drug and, ideally, function autonomously for years.

Most areas of engineering are beginning to benefit from MST, through either the development of novel products or improvements in existing products, e.g. the airbag crash sensor. Consumer electronics, mobile communications, automotive/traffic control, automation, aerospace, medical, environmental and the household have been identified as markets which will be revolutionised by MST products.

Several market surveys have been undertaken in recent years to assess the current scale, growth potential and product range for microengineering. At present the world-wide multi billion dollar per annum MST industry is dominated by inkjet printers and read/write heads for hard disk drives. Micropressure sensors, and micro-accelerometers (e.g. airbag sensors) are also key components set to rise significantly by volume. The MST industry turnover will continue to grow and be typified by such products as microsensors for chemical and biological/biomedical analysis, drug delivery systems, waveguides and switches for telecommunications and micromachined flat panel displays.

Table 2-2 shows some areas of applications where microengineering techniques are used and Table 2-3 illustrates some products with MST attributes.

Aerospace	Instrumentation
Automotive	Medical and biomedical
Consumer products	Process control
Domestic household	Safety and security
Entertainment, e.g. toys	Telecommunications
Environment monitoring	Utilities monitoring - water, - electricity, gas
Information technology - peripherals	
Vibration monitoring	Imaging

Table 2-2 MST Applications

Flat panel displays	Optical components
Force microscopy tips	Position measuring devices
Gyroscopes	Read/write magnetic heads
Hearing aids	Sensors for - acceleration - fluid flow - chemicals (gases, liquids) - temperature - pressure
Inkjet printers	
Micromotors	
Micropumps, microvalves, microfilters	
Microspectrometers	
Microwave detectors	
Nebulisers	Thin film resonators for filters
Infra-red sensors	Microwave components, switches

Table 2-3 Products with MST Attributes

2.1.3. Why MST?

MST will bring to aerospace many of the advantages associated with any new technology. A useful model is the semiconductor industry where unprecedented performance has been achieved over the last 40 years and where many novel products have been produced.

A major attraction of MST is its ability to produce devices of significantly improved performance such as accuracy, operating speed and sheer complexity. This will be true, particularly for micromechanical devices (eg accelerometers), when associated with embedded analogue and/or digital circuitry.

Partly because MST has been derived from the semiconductor industry, significant manufacturing cost reductions are possible. For example, high yield processes, batch processing techniques and at least partial self-assembly all lead to lower manufacturing costs.

MST also lends itself to much improved design techniques, particularly when small size is associated with batch processing. For example, a simple silicon surface microengineered device may occupy an area of 1000x1000 micron or less and produce more than 10000 devices per wafer. Thus during the design phase of a device, many engineering variants may be manufactured at the same time and under exactly the same processing conditions. This can lead to much cheaper Non-Recoverable-Engineering costs and ultimately faster time-to-market for a product.

Probably the ultimate value of MST devices lies in their novelty and in that the combination of performance, complexity, size and cost cannot be met by any other technique. The most outstanding example today is the silicon chip, which of course contains no micromechanical elements. A unique aspect of microsystems is the increased functionality that can be obtained by combining the small micromachined structures with sensing and actuating materials. These include piezoelectric materials such as $PbZr_xTi_{1-x}O_3$, ZnO or AlN, magnetic materials and shape memory alloys. Most of these materials can be prepared as bulk components however full advantage is taken of their properties when they are incorporated as thin films on micromachined structures. In view of the advantages suggested above, it is not surprising that many areas of technology are exploiting MST where small size as such is not a prerequisite, eg in the automobile industry. However, aerospace will clearly benefit as both weight reduction and increased function complexity have obvious advantages for planetary exploration and deep space probes.

2.2. MST TECHNOLOGIES

MST requires supporting technologies similar to those for macroengineering, for example, design, modelling and simulation, new materials, new assembly methods and testing. In MST, many of these supporting technologies are at a very early stage of development. However, the key to MST is the microfabrication technology, initially adapted from the semiconductor industry but now being developed in new directions.

Much of the pioneering fabrication technology for MST has been based upon silicon and hence silicon processing manufacturing techniques. Silicon process compatible materials such as SiO_2, Si_3N_4 and polysilicon have been widely used, along with conventional silicon processes such as photolithography, ion implantation, chemical vapour deposition (CVD) and reactive ion etching. However, the development of MST will require a wider range of materials to be available, eg ceramics, plastics and consequently new microfabrication techniques will need to be employed.

New process and materials will also need to be developed to integrate new functional materials into microsystems. Structures 2-3 orders of magnitude thicker than have been achieved with current silicon technology will be required if many electromechanical concepts are to be realised.

As the basic principles of semiconductor and opto-electronics are well documented elsewhere, emphasis here is given to microfabrication techniques particularly suitable for micromechanical structures.

2.2.1. Basic Pattern Generation

Most of the microfabrication techniques for both microelectronics and micromechanics start with a 2D pattern which in some manner is etched into the bulk of the substrate to give the third dimension. Pattern generation for MST can be derived directly from maskmaking as developed for the microelectronics industry. Data starts with a computer-aided design system, which produces the required layout. This data is then presented to a pattern generator, such as an electron beam machine, which will either produce a mask to be used subsequently in some form of projector or can write directly on the substrate if it is suitably flat. The mask generated by the electron beam generator can be projected by a stepper with a typical reduction of 5X, to make high resolution step and repeat images.

2.2.2. Bulk micro-machining

Bulk micro machining is often described as a subtractive process, where the bulk of the substrate (usually glass or single crystal silicon) is etched, cut, or otherwise modified to make the desired structure. The substrates can be machined by numerous techniques including isotropic etching, anisotropic etching, electrochemical etching, spark machining, mechanical milling, ultrasonic milling, laser and laser-assisted etching, and electro-discharge machining. A second definition of bulk micro machining would be the formation of a desired microstructure by using the bulk of a substrate. This second definition may be more appropriate, since it is inclusive of wafer bonding technology. The most widespread techniques for bulk micromachining are wet anisotropic etching and wafer bonding. Bulk micromachining is a technique that permits to create suspended microstructures by chemically etching the substrate. We can say that it is a volume etching because the chemical action creates a cavity into the substrate. This technology has been used until now, only for micro-electronic industry. Wet chemical anisotropic etching of silicon is one of the key technologies of silicon micromachining. Opposed to ”surface micromachining”, where structures are fabricated from thin films that are released by films of a material that can be removed without attacking the structural material, wet chemical anisotropic etching is also referred to as “bulk micro-machining”, because in this technology the body of the silicon wafer is etched away.

The anisotropy of the etching systems from the crystal structure of silicon, and the shapes that can be performed by bulk micromachining are restricted to those that are bounded at least in part by slowly etching planes. The etching speed (expressed in µm/mn) depends on the crystallographic orientation of the surface in contact with solution. This is dominantly the family {111} planes. Silicon wafers with a surface oriented in either <001> or <110> are covered by a thin film of material that is etched much slowly in the solution used for etching silicon, openings in this film are defined by standard photolithographic techniques, and the sample is immersed into the etchant. Figure 2-2 shows a speed etch polar diagram of silicon into a 10 % TMAH (tetra-methyl ammonium hydroxide). We can say that the etching speed in the <111> plane is very slow but not null in front of the other planes.

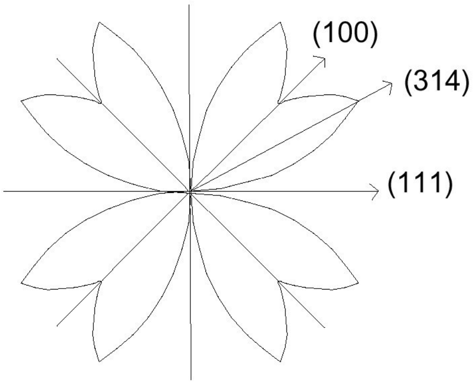


Figure 2-2: TMAH etching speed polar diagram

The anisotropy character of silicon etching is of great technological importance. An opened mask neatly aligned along crystallographic orientations allows the precise control of the shape and the dimensions of the microstructures. The technology is now being used to fabricate pressure, force, flow, and acceleration sensors using the advantages of the batch processing. That is why, if the market demands these devices in large numbers, the production costs can be fairly small. Single crystalline silicon has some remarkable mechanical properties, making this material attractive for mechanical device. We will see these properties in the next section. In bulk micromachining, 2 techniques can be used: etching from the front-side or etching from the backside. Front side micromachining enables to design easily suspended structures without supplementary photolithography. Backside micro machining needs a supplementary stage of photolithography.

2.3. MECHANICAL PROPERTIES OF SINGLE CRYSTALLINE SILICON

As we have said previously, single crystalline silicon has a number of remarkable mechanical properties. Being a semi-conductor, the chemical binding between the Si atoms is covalent. This contrasts with metal binding potentials, and consequently, crystal dislocations are much more movable in metals than in semi-conductor materials. Metals are ductile whereas semiconductors are brittle. But single crystalline silicon can be made perfectly – virtually without any defects. Being loaded, there are no dislocation lines that are able to move, and the introduction of new dislocation line would immediately cause a crack in material – silicon would break. At room temperature, single crystalline silicon can only be elastically deformed. The yield strength of silicon is extremely high. It is comparable in strength to stainless steel. It makes silicon a material superior to any metal in many applications. The elastic deformability is most impressive in microstructures. Figure 2-3 shows a SEM picture of an etched silicon beam heavily loaded by a stylus. If the load is released, the beam will return to its original shape.

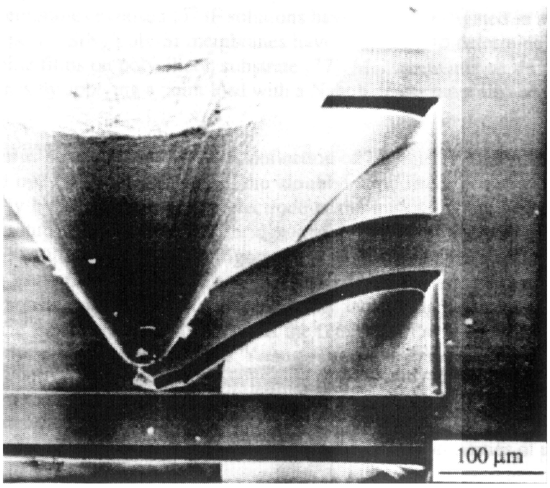


Figure 2-3: SEM picture of an etched silicon beam heavily loaded by a stylus force (from [9])

Under certain conditions, in particular at elevated temperature, it can be mentioned that plastic deformation of single crystalline silicon has been observed. This observation, however, has little practical impact on silicon micro-mechanics. If a piece is loaded even well below the yield strength, the material deforms quickly. But after this deformation, the piece continues to deform at a much larger time scale, which is measured in minutes. The deformation is reversible: if the load is removed, the materials regains nearly all its original form and dimensions quickly and continues to deform until the original form is exactly reached. This phenomenon is called creep.

2.3.1. Properties of anisotropic etching solutions

There are a number of wet etchants that etch silicon anisotropically. All of them have merits and drawbacks. The most important are hydroxides such as KOH, NaOH, CeOH, RbOH, NH_4OH, TMAH, and mixtures called EDP (ethylendiamine, pyrocatechol, and water). We will concentrate on the KOH, EDP and TMAH (tetramethyl ammonium hydroxide).

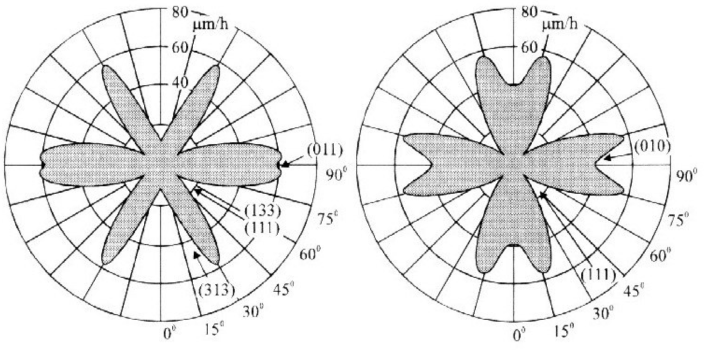
In the final choice of etchant, a number of issues have to be considered:

- Etch rate,
- Topology of the etch ground,
- IC compatibility,
- Etch stop,
- Etch selectivity of others materials,
- Mask material and thickness of the mask.

2.3.1.1. KOH solutions

It is the most commonly used etchant. It is much less dangerous than other etchants, easy to handle, readily available, and fast etching. The worst disadvantages are that KOH is IC incompatible and that the selectivity to oxide is rather poor. Compared with EDP, KOH is disadvantaged regarding oxide selectivity– EDP etches oxide slower than KOH by a factor of 100.

In Figure 0-4, we can see the lateral etch rates as a function of orientation on <100> and <110> wafers. We can note the minimum rate on the <111> plane.



(a) (b)

Figure 0-4: Lateral etch rates as a function of orientation 50%KOH solution 78: (a) <110> and (b) <100> silicon wafers (from [9])

2.3.1.2. EDP solutions

As previously mentioned, the advantages of EDP are its selectivity towards oxide and its lower etch rate of B+-doped silicon. Therefore the HF dip just before etching is crucial, otherwise the native oxide will prevent any etching. In contrast to KOH, very few bubbles are emerging.

For EDP, there are standard concentrations; either for use as a fast etcher or for use as a slow etcher at lower temperatures. Underetch rates are given in Figure 2-5. Generally, <100> and <110> planes of silicon are etched slower in EDP than in KOH. A further difference is that the minimum at <111> is much steeper in EDP. This has the practical consequence that it is much more important when etching in EDP to align the crystallographic direction more precisely than when etching in KOH.

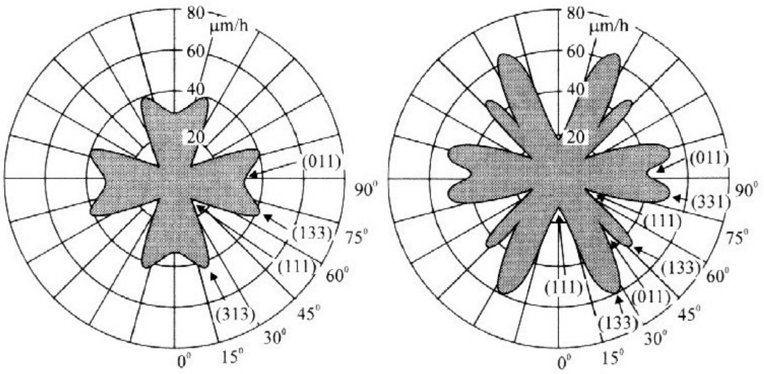


Figure 2-5: Lateral underetch rates as a function of orientation. EDP solution (a) <110> and (b) <100> silicon wafers (from[9])

2.3.1.3. TMAH solutions

One of the most important advantages is that TMAH is an organic material, so it does not contain any metal ions, making TMAH IC-compatible etching agent. Though KOH solutions have been made commonly used as an anisotropic etchant, TMAH aqueous solution, despite its expensive cost, has been gradually introduced in industry and is replacing KOH solution. It hardly attacks the silicon dioxide film used as an etching mask and it does not contain harmful ions that might damage the electrical circuits that are integrated with micromechanical structures on the same chip.

Etching rates of single crystal silicon in both KOH and TMAH solutions has been measured in [1]. Hemispherical specimens have been used and their anisotropy etching properties have been compared:

- The etching rate ratio of <111>/<100> in TMAH is about twice than in KOH.
- The etching rates depend on the concentration of KOH and TMAH.
- The effects of etchant circulation can be ignored for KOH, but not for TMAH solutions.

2.3.2. Etching mechanisms

The etching mechanism is composed of different phases detailed below:

- To remove material in selected areas, the surface needs to be protected elsewhere: silicon dioxide (SiO_2) is a chemically resistant material easily formed by heating the wafer in an oxygen atmosphere. Covering the oxide with a light-sensitive film, called “photoresist”, can pattern the oxide.
- The photoresist is exposed to UV-light in selected areas through a photographic mask. The exposed photoresist is easily removed revealing the underlying oxide.
- This oxide can, in turn, be removed by hydrofluoric acid (HF) that does not etch silicon significantly.

If the wafer is now exposed to a reactive etchant, unprotected silicon atoms are removed, while the atoms protected by the oxide layer are left unaffected.

2.3.2.1. Etch stop mechanisms

A SiO_2 layer covering the silicon surface protects it from being etched. Another way of protecting the surface is to deposit a silicon nitride layer using CVD (Chemical Vapor Deposition). This layer is even more hardened to most chemicals and etchants, such as HF and KOH. However, this hardness implies more complex patterning and removal processes.

Surface protection is often sufficient, but for some structures you need to treat parts of the silicon material itself to render it inert to the etchant, e.g. when etching beams and membranes. It can be accomplished by doping the material heavily with, for example, boron. Silicon, boron-doped to around one atomic percent, is not etched by most etchants. A thin beam with a controllable thickness can be produced in this way if the wafer is doped in a beam pattern from one side. Etching the wafer from either side then reveals the beam since the doped areas are left intact.

There is a more subtle way of dopant selective etching. If a wafer has areas of both p- and n-type, and the wafer is biased with a certain electric potential relative to the etchant, the p-type material is removed, while the n-doped areas are left unetched.

2.3.2.2. Examples and applications

In this part, we will show some applications of anisotropic etching and bonding. On one hand, the technology required to fabricate these devices will be shown and on the other hand, the working of the devices will be qualitatively explained.

Figure 2-6 shows some structures that can be manufactured thanks to bulk micromachining. The suspended structure can be bridges (a), beams (b) or membranes (c).

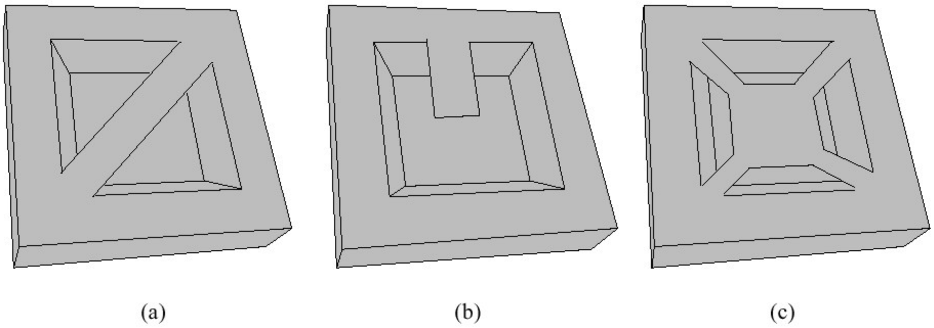


Figure 2-6: Examples of front-side bulk micromachined structures (from [2]).

Membranes are used in different types of micro-systems. Some examples of these types of micro-systems are pressure sensors, microphones and pumps. All these devices use membrane technique to operate. We will focus on types of micro-systems most likely to be used in the space environment. That is why, we will develop the case of the pressure sensors because there have been many research activities on this type of devices.

Beams are used in several ways in micromechanical devices. It can be used to suspend membranes or masses in accelerometers, as resonating strain gauges in mechanical sensors, as actuators. The beams are the solution to minimize heat transfer generated by the suspended part of the device.
Here are some devices fabrication and actuation.

2.3.2.3. Pressure sensor

There are many types of pressure sensors. The most important ones are: capacitive, piezoresistive, resonant and optic.

A capacitive pressure sensor uses the deflection of a membrane that changes the measured capacitance. The typical value of this type of capacitance is 10-100pF, and its change by a deflection is a fraction of this value. There are a lot of capacitive pressure sensors examples. A typical bulk micro-machined capacitive pressure sensor is shown in Figure 2-7.

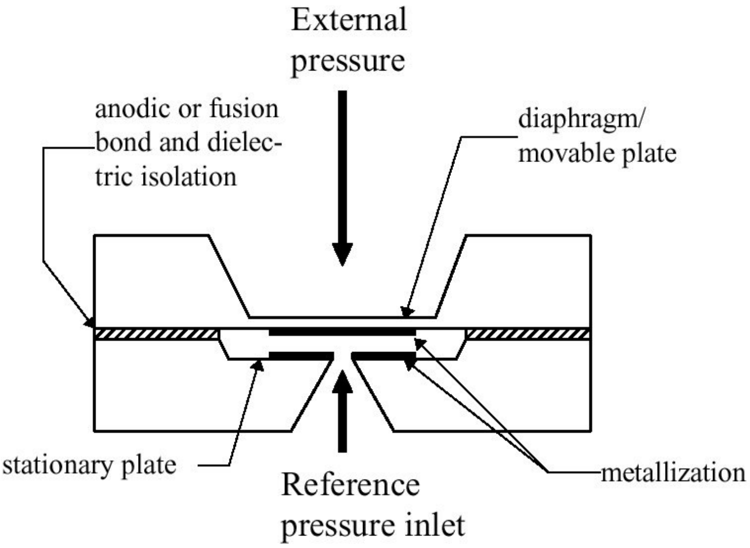


Figure 2-7: Cross section schematic of bulk micro-machined, capacitive pressure sensor [3]

Historically, capacitive sensors have taken benefits from the same advances in diaphragm etching and wafer bonding than piezo-resistive sensors. However, the piezoresistive approach generally has a complex transducer with simple circuit requirements, while the converse is true of the capacitive approach. For this reason, capacitive sensors have benefited more from advances in circuit design than piezoresistive sensors [4].

<u>Piezoresistive pressure sensors</u>: The deflection of the membrane is measured thanks to strain gauges. A schematic of the piezoresistive pressure sensor is shown in Figure 2-8:

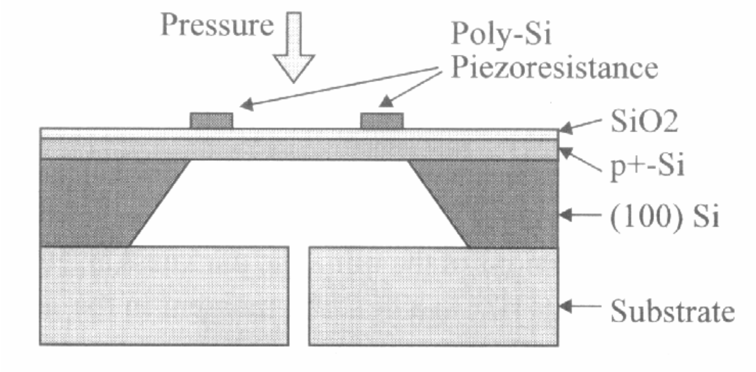


Figure 2-8: Schematic cross section of a pressure sensor with polycrystalline silicon piezoresistive elements (from Heuberger [5])

Motorola has designed the MPX200 BM piezoresistive pressure sensor [6]. The Motorola MPX200 fabrication [7] sequence is shown in Figure 2-9. First, the silicon substrate is selectively ion implanted to form the transducer (Figure 2-9-a). Then, the metal contacts are deposited and patterned, and the surface is passivated with a silicon nitride film (Figure 2-9-b). Finally, the sensor wafer is bonded to a handle wafer to form a reference pressure cavity (Figure 2-9-d) if the device has to measure absolute pressure.

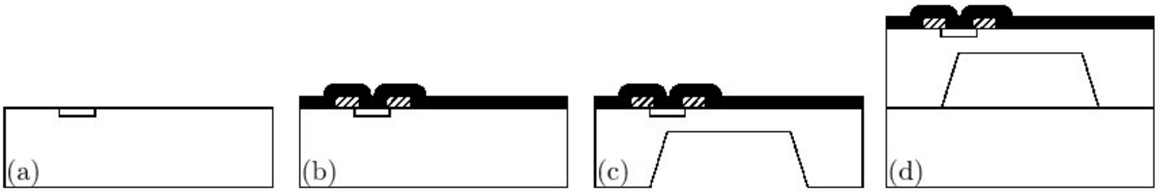


Figure 2-9: Fabrication sequence for bulk micromachined sensor. (a) Ion implant transducer. (b) Deposit and pattern metal contacts, passivate with silicon nitride. (c) Etch backside of wafer to form diaphragm. (d) Bond handle wafer to sensor wafer to form reference cavity.

Resonating pressure sensors : A new type of pressure sensor has been reported in recent years: the resonant beam pressure sensor. The sensors operate by monitoring the resonant frequency of an embedded doubly clamped bridge [8] or comb drive [9] as shown. The resonant beam, which has also been called a resonating beam force transducer, acts as a sensitive strain gauge. As the stress state of the diaphragm changes, the tension in the embedded structures changes and so does the resonant frequency.

There have been several mechanisms reported by which the structures can be driven into resonance while the resonant frequency is sensed. One method is electrostatic drive–piezoresistive sense. The structure is driven to resonance by AC applied voltages, and the resonant frequency is measured by piezoresistors. Structures can also be optically excited by laser and sensed by a photodetector, or electrostatically excited and capacitively sensed. Resonant pressure sensors have been shown to exhibit better pressure sensitivity and lower temperature sensitivity than pure piezoresistive sensors. Furthermore, a frequency output is more immune to noise than classical analog piezoresistive and capacitive signals.

An example of resonating pressure sensor is described in [10]. The working of this resonant pressure sensor is based on the fact that a change in the form of the body will induce different moments of inertia and resonance frequencies. We can see in Figure 2-10-a the sensor. Two diaphragms are bonded together in order to form a cavity. The resonance frequency will change if a difference of pressure inside or outside the cavity appears. On the Figure 2-10-b, we can see the manufacturing steps of the sensor. In the first step, the membrane and part of the trench separating the cavity from the support were etched in EDP. Then, an oxide was grown in order to protect the membranes from the second etch step, in which the etching of the trenches was completed. Direct silicon bonding was finally used to bond the wafers.

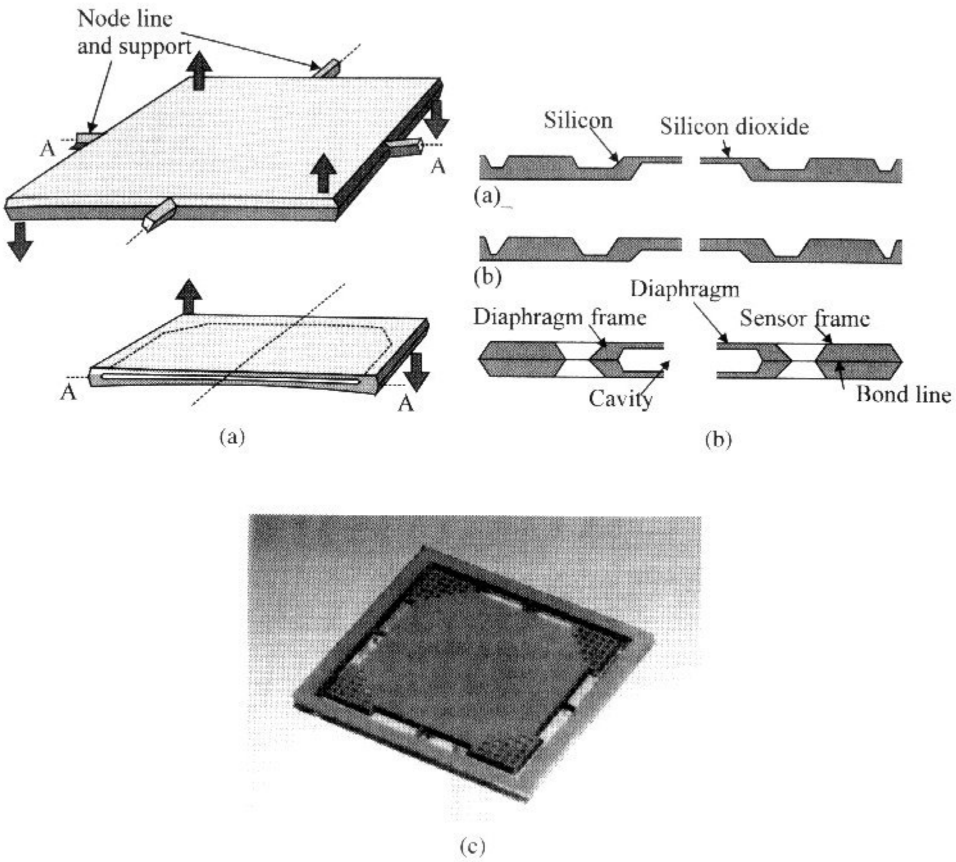


Figure 2-10: (a) Design of a balanced resonant pressure sensor. Heavy arrows indicate mode of vibration.

(b) : Fabrication sequence of the balanced pressure sensor.
(c) Photograph of the complete resonant pressure sensor. From [11].

2.3.2.4. Accelerometers

High precision accelerometers are widely used in applications such as inertial navigation. Recent advances in fabrication technologies for microaccelerometers have made mass production of these devices with low/medium sensitivity possible.

Mechanical devices fabricated with traditional bulk micromachining are usually formed with long time anisotropic wet etching, with silicon etching solutions such as KOH or TMAH. The anisotropy provided by these wet etchants is bound by silicon crystal planes, and therefore limits the possible shapes of mechanical structures and makes the mechanical structures occupy large chip areas.

A new kind of laterally sensed accelerometer has been fabricated with two mask bulk processes [12]. It does not need aligning bonding technology. The use of the glass wafer makes the parasitic capacity minimal.

Figure 2-11 shows the schematic technology sequence.

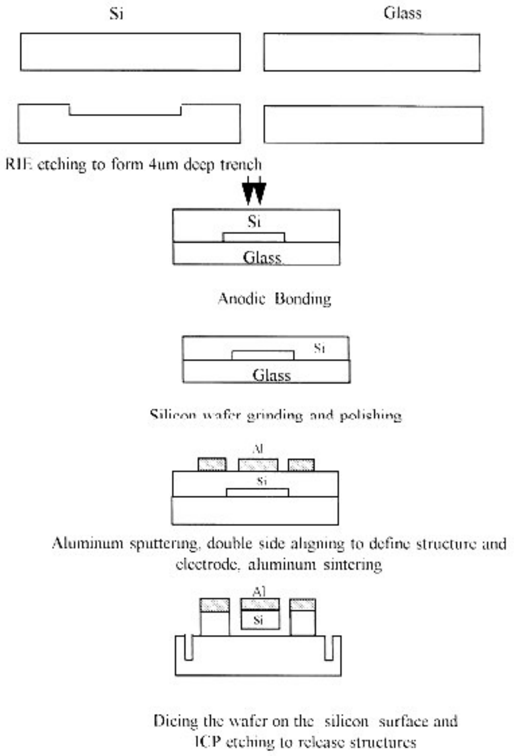


Figure 2-11: schematic technology sequence (from [12])

The technology starts from wet etching to form a 4 μm deep trench on the silicon wafer followed by anodic bonding with a thick bare Pyrex glass. The new obtained silicon wafer surface was then sputtered with 1μm thick aluminum followed by etching to release structures. Then, the wafers were diced from the silicon surface.

Figure 2-12 shows the vertical view of one cantilever accelerometer fabricated with this technology.

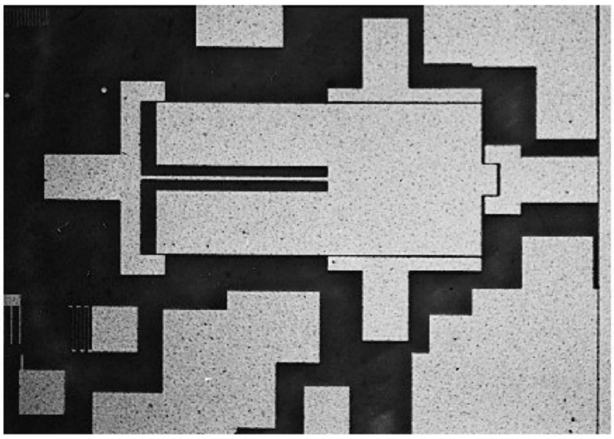


Figure 2-12: Vertical view of one cantilever accelerometer fabricated with the technology (from [12])

The accelerometer is composed of one movable cantilever, 3 stationary electrodes and one movable mass. The mass was fixed on the glass through the cantilever. The accelerometer fabricated with this technology shows a sensitivity of 1.85 V/g, a linear coefficient of 99.99%. The accelerometer can also afford 4500g.of acceleration of 0.2ms duration.

2.3.2.5. Vibrating sensors like microgyrometers

In Figure 2-13, a successfully developed micro-vibratory gyroscope with vacuum package is presented. The vibratory structure of the gyroscope is a rotational disk and it can detect two-dimensional angular rates simultaneously. The structure of this device is fabricated by bulk micromachining. The advantage of this technique is the possibility of obtaining a heavy mass structure and low acceleration sensitivity.

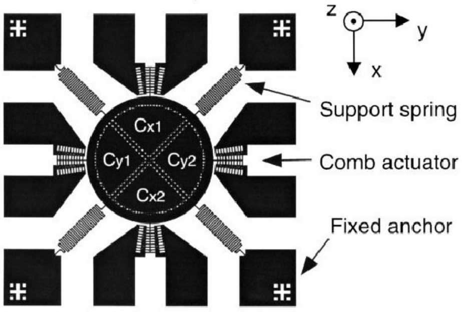


Figure 2-13: silicon vibrating structure (from [13])

In the this scheme, we can see the silicon vibrating structure where the rotational vibrating disk is supported by four springs. Four detection electrodes are deposited on the glass for individual axes detection. Comb actuators apply a reference vibration at the fringe of the disk. The disk vibrates rotationally at the resonance frequency.

When an angular rate is applied about the X-axis, the associated Coriolis force produces a displacement of the vibrating plate. The displacement is detected by capacitance change and is treated by an ASIC chip.

The silicon nitride is deposited and patterned for the following local oxidation step.

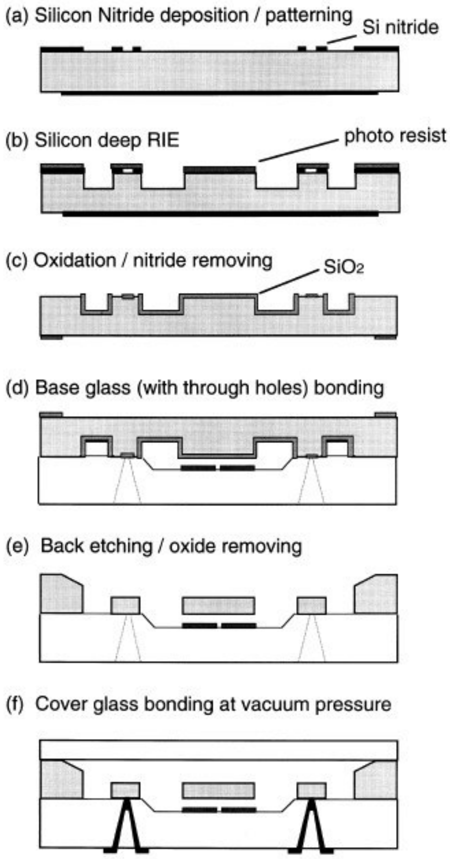


Figure 2-14: fabrication process

- Deep RIE forms silicon vibrating disk, support springs and electrostatic comb actuators.
- A layer of local oxidation is deposited to protect against unnecessary etching.
- Then, the silicon structure is bonded with the base glass.
- The backside of the silicon is etched out by wet and dry etching and the remaining oxide is removed.

2.3.2.6. *Micro-valves for space application*

The development of a JPL micro-valve has been reported on [14]. These kinds of micro-valves can be used for space applications, such as micro-propulsion, in-situ chemical analysis of other planets. This JPL micro-valve is expected to have an extremely low leak rate, limited susceptibility to particulates, vibration or radiation, as well as a wide operational temperature range.

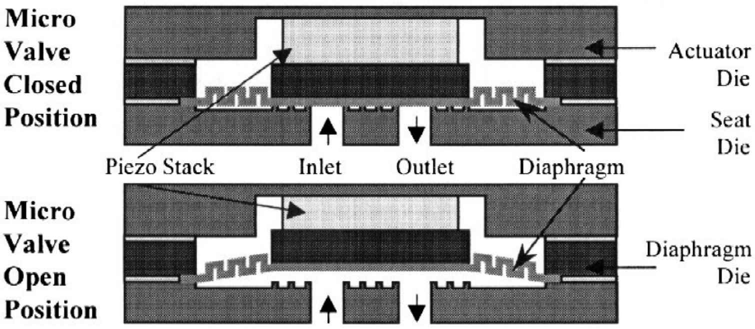


Figure 2-15: Micro-valve cross-section (from [14])

Figure 2-15 shows this micro-valve. The valve begins as three separate parts: the seat, the diaphragm and the actuator. The base of the valve is the seat that will interface with the rest of the micro-fluidic system. It also contains the inlet and the outlet. The center section of the valve is the diaphragm wafer. It has a circular corrugated diaphragm, with a circular boss in the center, covering both openings in the seat. The actuator consists of a piezo-electric disk in rigid housing. Gold-to-gold thermo-compression is used to bond all three parts.

The dimensions of the diaphragm and seat are 16mm by 16mm by 0.4mm. The pieces are bulk micromachined from n-type silicon wafers. In order to create circular shapes, DRIE technique was used.

Process fabrication for the seat diaphragm part is [14]:

- Seal rings and corrugations are etched into seat and diaphragm wafers, respectively.
- Patterning and DRIE etching from the backside to fabricate the inlet and the outlet.
- A low stress 1μm thick silicon nitride membrane is grown over all surfaces of both wafers.
- Boss is released using DRIE etching from top of diaphragm wafer.
- Metal is evaporated onto the bonding surfaces and patterned to create bonding areas.
- The backside of the diaphragm wafer is patterned and etched to release the boss.
- The wafers are bonded.

Presently, only seats and diaphragms have been fabricated and assembled.

2.4. SURFACE MICRO-MACHINING

2.4.1. Surface micromachining principle

Surface micromachining is also known as "sacrificial layer etch".

Surface micromachining techniques build up the structure in layers of thin films on the surface of the silicon wafer (or any other suitable substrate).

The process would typically employ films of two different materials, a structural material (commonly polysilicon) and a sacrificial material (oxide). These are deposited and dry etched in sequence. Finally the sacrificial material is wet etched away to release the structure. The more layers, the more complex the structure, and the more difficult it becomes to fabricate.

"Bulk micro machining" term is opposed to "surface micro machining" because the silicon bulk is not etched in the surface micro machining technology.

Surface micro machining is a technique that enables to design mechanical structures with more freedom than bulk micro machining. The biggest drawback of surface micro machining is the restriction to thin films. However, during the last few years, more and more microsystems have been designed with surface machining of thicker films. It can be possible with the help of alternative ways for photolithography. Surface micro machining using thicker structures became possible with the same precision as machining of thin films using conventional photolithography.

The majority of the surface micro machining work has focused on the combination of polysilicon as the structural material and silicon dioxide or related glasses as the sacrificial material that is etched in HF solutions.

Polycrystalline silicon (often termed poly silicon, or poly) is an ideal material from which to make MEMS. Its mechanical properties are excellent: it is stronger than steel (polysilicon has a strength of 2-3 GPa, depending on surface flaws; while steel has a strength of 200MPa - 1GPa, depending on the process parameters), is extremely flexible (the maximum strain before fracture is ~0.5%), and does not readily fatigue. Most importantly, polysilicon is directly compatible with modern IC fabrication processes. In fact, polysilicon is currently used in virtually all IC fabs as the primary material comprising the gate electrode of transistors.

We can see in Figure 2-16 the basic fabrication steps:

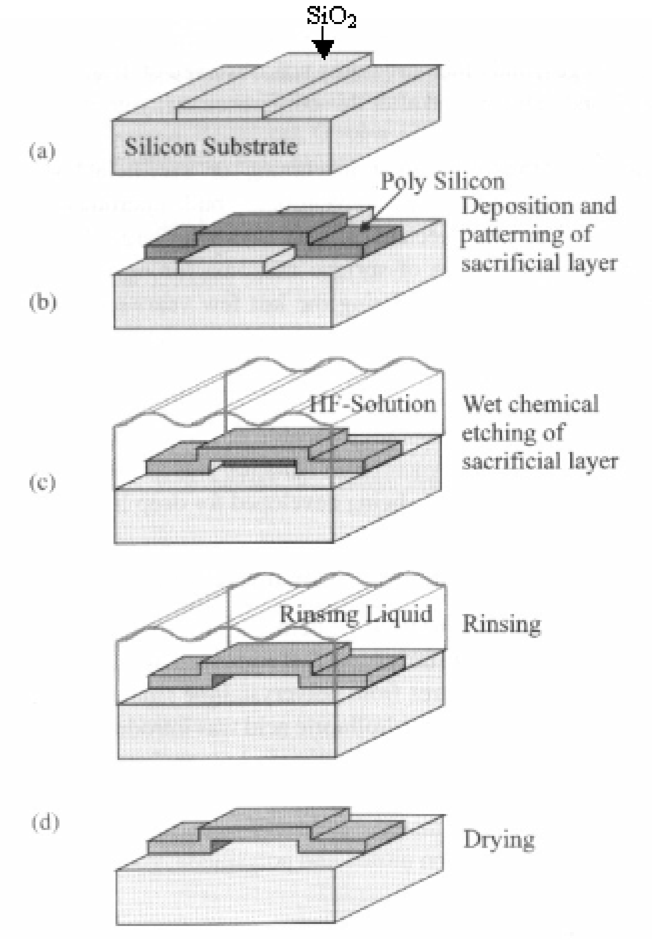


Figure 2-16: Basic process of surface micro machining. [11]

The process steps are the following:

- A sacrificial layer of oxide is deposited on the surface of the wafer.
- A layer of polysilicon is then deposited, and patterned using Reactive Ion Etching (RIE) techniques.
- The wafer is then wet etched to remove the oxide layer.
- The last steps are raising procedures to remove the fluoric acid and drying from the rinse liquid.

For the growth of the thin films, good step coverage is important. This is achieved in LPCVD (Low Pressure Chemical Vapor Deposition) processes. Furthermore, a sacrificial layer that etches fast is advantageous. Phosphorous-doped silicon dioxide (PSG) meets this requirement. It follows that besides the usual equipment for micromachining, LPCVD equipment for polysilicon and PSG is required.

We can see on the Figure 2-17 a microsystem before and after sacrificial layer etching.

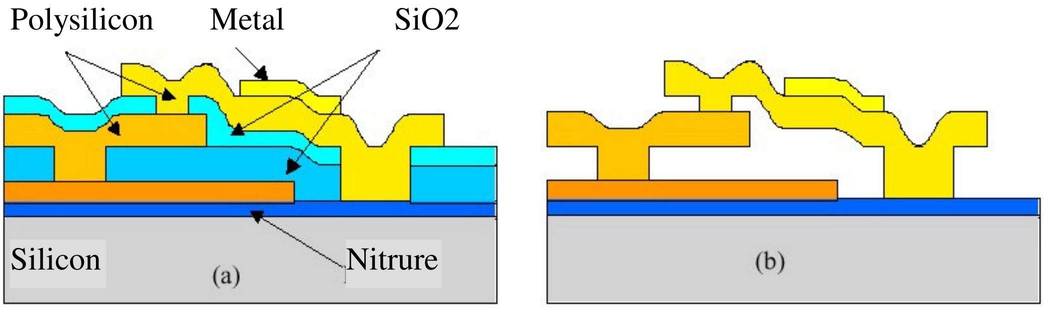


Figure 2-17: Surface micro machined system before and after sacrificial layer etching

Sacrificial layer etching is generally done by wet hydrofluoric acid for the polysilicon/silicon dioxide combination. This process uses the isotropic nature and high selectivity of wet etching to release the overlying structural polysilicon films.

There are three key challenges in fabrication of microstructures using surface micromachining:

- Control of stress and stress gradient in the structural layer to avoid bending or buckling of the released microstructure. The mechanical properties of thin films strongly depend on process parameters and thermal treatment. As deposited, the polysilicon films are under a strong compressive stress. When such films are released by sacrificial layer etching, they may buckle. We can see an example of buckled polysilicon structures in Figure 2-18.

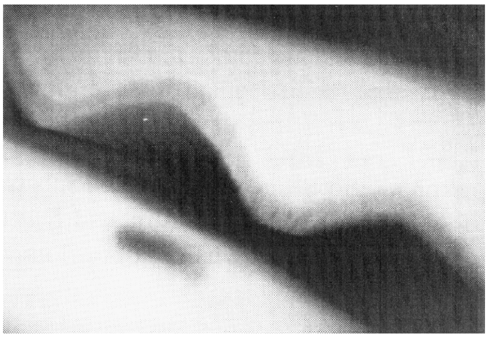


Figure 2-18: Buckled polysilicon structures

- High selectivity of the sacrificial layer etchant to functional layers.
- Avoidance of stiction of the released microstructure to the substrate. It has been found that if the thin film structures come into contact with the substrate, they stick to it and there is no chance of freeing them. When microstructures are dried, a meniscus appears between the different levels of the microstructure. This causes an attractive force between substrate and thin film. As a result, the structure collapses. By this collapse, the thin film and the substrate approach each other so close that other forces like Van der Waals forces, electrostatic forces appear, resulting in permanent attachment of the structures of the substrate.

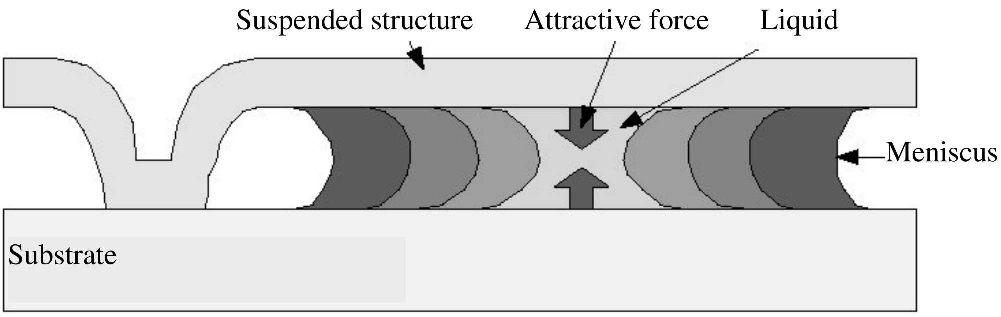


Figure 2-19: Attractive force due to meniscus during drying

There are some methods to avoid this phenomenon. One solution is to use hydrophobic agent on the structures like alkysilanes to avoid meniscus apparition. Another solution is avoiding phase transition between liquid state to gaseous state. It is possible by sublimation of solid phase.

After etching of the micro mechanical silicon structures, they have to be released. Many techniques have been studied. Generally, in surface micromachining, a glass layer is used as a sacrificial layer that is etched using wet or vapor etchants. But there is a problem called sticking due to surface tension liquids, and many solutions have been proposed to solve this problem. These solutions are SCREAM, SIMPLE and BSM-ORMS processes. These techniques are self-aligned and are suitable for batch fabrication. In fact, the release of the structures takes place in the gas phase, so there is no liquid phase responsible for stiction.

2.4.2. Examples of applications

In this part, we are going to see some examples of surface micromachining applications that can be used in space.

Surface micro machining has enable some large companies such as Bosch or Analog Devices to sell some microsystems based on this manufacturing technology. For a number of structures, in particular for the famous micromotors, no real application has been anticipated so far. That is why; we will only focus on microsystems that can be used in space.

2.4.2.1. Vibrating gyroscope

A vibrating microgyroscope with a thin polysilicon resonator was fabricated using silicon surface micromachining [15]. This type of microgyroscope is simple compared to other types, and it has no rotating parts. The structure of this microgyroscope is presented on Figure 2-20. A polysilicon resonator 400µm wide, 800µm long and 5µm thick is suspended by four beams whose ends are anchored on a single crystal silicon substrate.

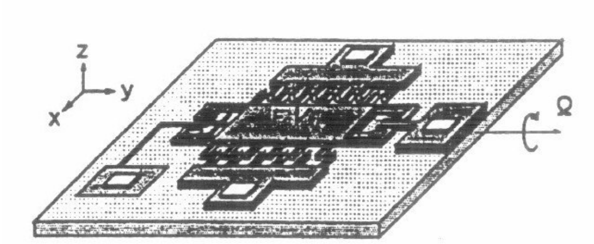


Figure 2-20: Schematic drawing of microgyroscope.

Figure 2-21 shows the fabrication sequence of the angular rate sensor.

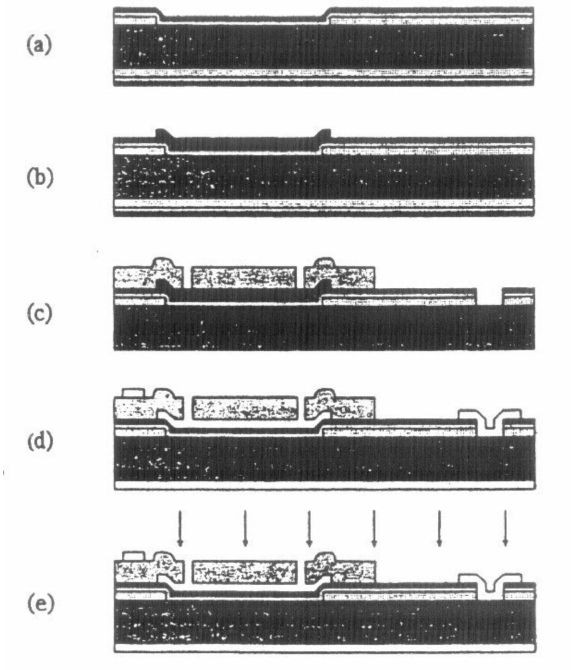


Figure 2-21: Fabrication sequence: (a) phosphor diffusion, (b) PSG deposition and etching, (c) polysilicon deposition and etching, (d) sacrificial layer etching, (e) resonant frequency trimming by ion milling.

A p type silicon wafer was used as substrate. After doping phosphor into electrode areas, insulation layers of SiO2 and SiN were formed on the silicon surface. Then, a 1µm thick PSG layer was deposited by LPCVD as a sacrificial layer, whose thickness determines the gap between the resonator and the output detecting electrode on the silicon substrate. A 5 µm thick polysilicon layer was deposited by LPCVD, and etched by RIE into the features of the resonator. The sacrificial layer was then removed by wet etching with HF.

2.5. SURFACE AND BULK MICROMACHINING

2.5.1. Comparison of the two techniques

In this chapter, we will compare both techniques in order to know the advantages and the disadvantages of each one. Sandia National Laboratories has compared [7] bulk and surface micromachined pressure sensors.

The two pressure sensors that have been compared are the Sandia National Laboratories surface micromachined sensor and a commercially available bulk micromachined MPX200 BM sensor developed at Motorola.

One of the relative merits of both technologies are summarized in the following table:

Parameter	**Surface Micromachining**	**Bulk Micromachining**
Mechanical properties	Good	Superior
Cost at low volume	Fair	Good
Cost at high volume	Good	Fair
Dimensional control	Better	Good
CMOS integration	Good	Fair
Packaging	Fair	Fair
Size	Smaller	Small

Table 2-4: Comparison between surface and bulk micromachining

- Material properties of single crystal silicon used in bulk micromachining are superior to deposited films used in surface micromachined. Single crystal silicon has few defects. While single crystal silicon wafers are nearly stress free, polysilicon films can have a range of compressive or tensile stresses.
- Capital costs for bulk micromachined equipement are generally lower than surface micromachined costs. For high volumes, however, smaller die size of surface micromachined parts will tend to make them more economical.
- Silicon micromachining dimensions are generally smaller with lateral variations due to photolithography and etching and vertical variations due to deposition thicknesses.
- Surface micromachined devices are often said to be more compatible with monolithic CMOS integration than bulk micromachined parts (co-fabrication of MEMS devices and CMOS on a single substrate). Three reasons are responsible for this phenomenon.
    - Reluctance to allow parts potentially contaminated with potassium (from KOH etching).
    - Reluctance to allow processing of potentially fragile bulk micromachined substrates.
    - Backside fabrication is not common in CMOS foundries and is required for bulk micromachined.
- Surface micromachined parts will generally be smaller than bulk micromachined parts for similar performance. This is mainly because the subtractive techniques used for bulk

micromachined are less controllable than the additive techniques used for surface micromachining.

2.5.2. Examples of applications

2.5.2.1. *Microaccelerometer*

A novel all-silicon single wafer fabrication technology has been used to design high precision capacitive accelerometers [16]. This technology combines both surface and bulk micromachining to attain a large proofmass, controllable/small damping, and a small airgap for large capacitance variation. The microfabrication process provides large proofmass by using the whole wafer thickness, and a large sense capacitance by using a thin sacrificial layer.

Figure 2-23 shows the device structure obtained by this technology. The proofmass and its supporting rim are formed by bulk micromachining and have the whole wafer thickness. There are eight boron doped suspension beams, which are symmetric with respect to the proofmass centreline and result in low cross-axis sensitivity. The electrodes are polysilicon plates created on both sides of the proofmass and anchored on an isolation dielectric at the frame.

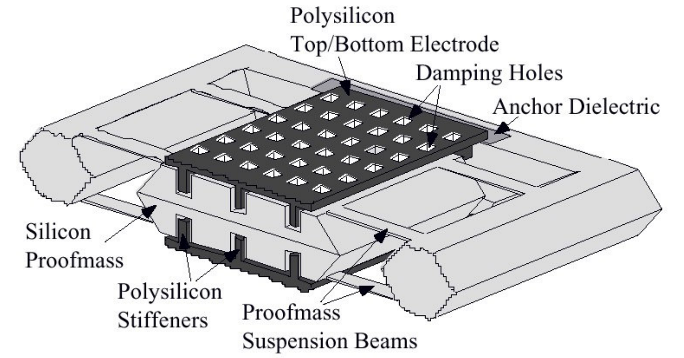


Figure 2-22: Micro accelerometer structure

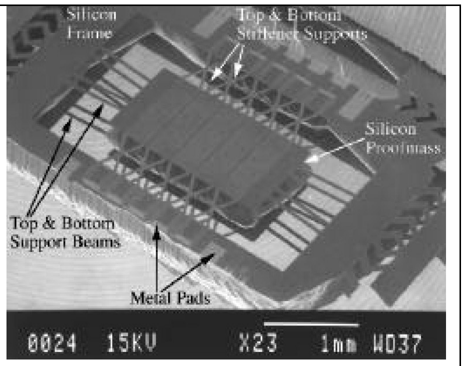
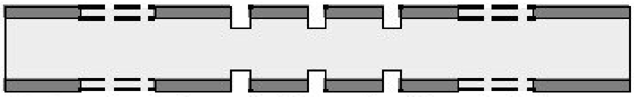


Figure 2-23: SEM view of the accelerometer

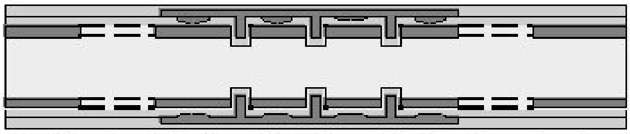
The fabrication process requires 8 masks, and is performed symmetrically on both sides of the wafer as shown in Figure 2-24.

A number of prototype microaccelerometers have been successfully fabricated using the presented technology. They achieve a high sensitivity, low noise floor, and controllable damping. All by using a single wafer process.

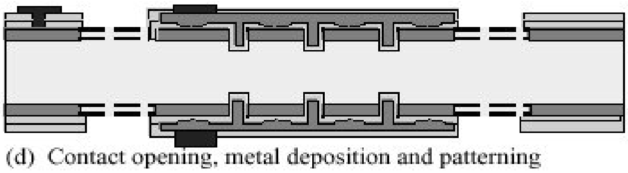
(a) Shallow boron diffusion to define beams, proofmass, and supporting rim. Nitride depositon and definiton for electrode anchors and isolation dielectric underneath electrode dimples.



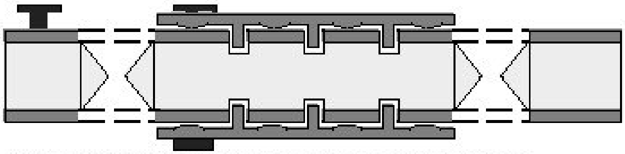
(b) Trench etch for vertical electrode stiffener definition.



(c) Trench refill using LPCVD sacrifical oxide and poly. Poly patterning to form electrodes and damping holes. Poly is sealed by a top LPCVD oxide layer. Dimples inside poly elecrode are created by partial etching of the sacrifical oxide before poly deposition.



(d) Contact opening, metal deposition and patterning



(e) Proofmass and rim formation by etching in EDP. Final proofmass release by etching the sacrifical oxide.

Figure 2-24: fabrication process sequence of the microaccelerometer

2.5.2.2. Vibrating ring gyroscope

This vibrating ring gyroscope presented in [17] consists of a ring, semi-circular support springs, and drive, sense and control electrodes. The ring is electrostatically vibrated into an elliptically-shaped primary flexural mode with a fixed amplitude. When device is subjected to rotation, Coriolis force causes energy to be transferred from the primary mode to the secondary flexural mode, which is located 45° apart from the primary mode, causing amplitude to build up proportionally in the latter mode; this build up is capacitively monitored.

We can see the structure of this gyroscope in
Figure 2-25.

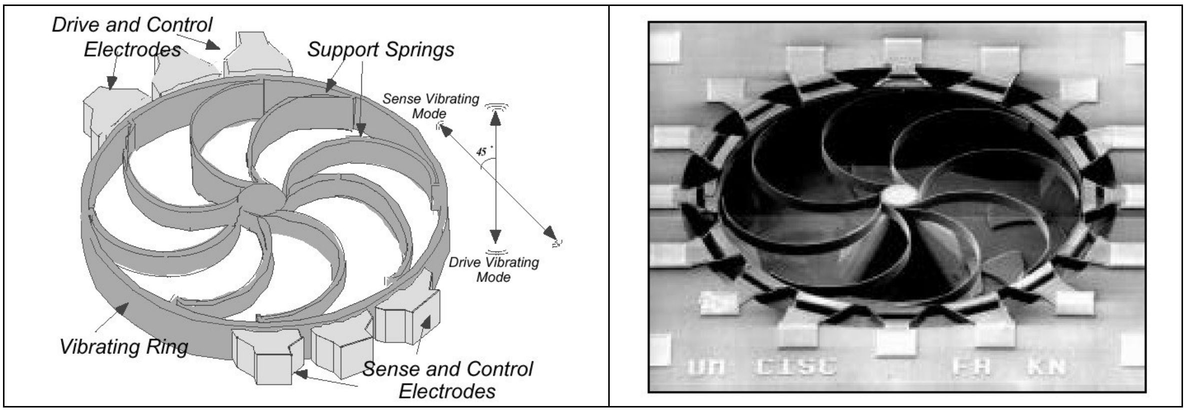
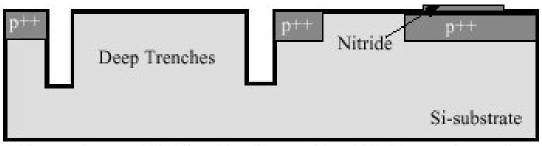
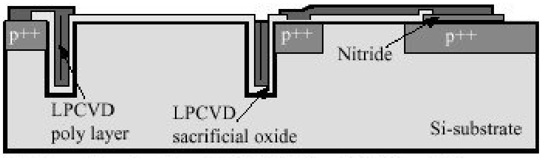


Figure 2-25: Structure (left) and SEM view (right) of the vibrating ring gyroscope [18]

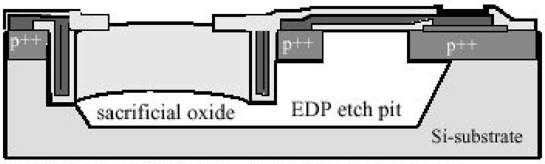
This gyroscope is manufactured using bulk micromachining and surface micromachining. The fabrication process requires seven masks and the sequence is shown in Figure 2-26.



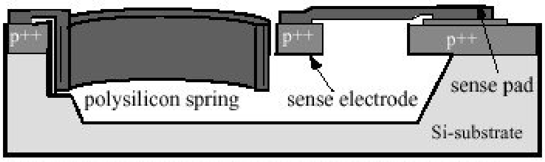
a) Deep boron diffusion (p++) to define the electrodes and support post; b) Deposit and pattern the isolating nitride layer; c) Dry etch deep trenches to define the ring structure.



d) Deposit and pattern the LPCVD sacrificial oxide layer; e) Refill trenches with structural LPCVD polysilicon layer (n-doped); f) Pattern the polysilicon layer.



g) Deposit and pattern the encapsulating oxide layer;
h) Deposit and pattern Cr/Au;
i) EDP etch to release and separate electrodes;



i) Etch the sacrificial oxide layer and completely release the structure.

Figure 2-26: Fabrication process for polysilicon ring gyro

The vibration ring and the support springs are created by refilling deep dry-etched trenches with polysilicon over a sacrificial LPCVD oxide layer. The depth of the trench primarily determined by the etching system used for its formation, can now be made to be as deep as several hundred microns. The ring-to-electrode gap spacing is defined by the thickness of the sacrificial oxide layer and therefore, it can be reduced to sub-micron levels, increasing the sense capacitance and hence improving the resolution of the device. The structural polysilicon layer is doped with phosphorous to lower its electrical resistance.

2.6. INTEGRATED SURFACE MICROMACHINING TECHNOLOGIES

Recently, a great deal of interest in manufacturing processes leads to the monolithic integration of micro systems with driving, controlling, and signal processing electronics. This integration allows improving the performance of micromechanical devices as well as reducing the cost of manufacturing, packaging and instrumentation of these devices.

As recently summarized in [19], mechanical structures require long, high temperature anneals to ensure that the stress in the structural materials of the micromechanical structures has been completely released. On the other hand, CMOS technology requires planarity of the substrate to achieve high resolution in the photolithography process. If the micromechanical processing is performed first, the substrate planarity is sacrificed. If the CMOS is built first, it (and its metallization) must withstand the high temperature anneals of the micromechanical processing.

A number of solutions attempt to address these problems. One is to fabricate the CMOS design using tungsten instead of aluminum, thereby allowing the chip to undergo a subsequent MEMS fabrication without adversely affecting the CMOS portion. In facts, the MICS process developed at UC Berkeley in the early 1990s, fabricates a modified p-well CMOS prior to polysilicon micromachining [20]. In order to raise the temperature ceiling of the CMOS, tungsten is used instead of aluminum for the metallization. $TiSi_2/TiN$ diffusion barriers prevent WSi_2 formation during the subsequent Si_3N_4 deposition at 830°C and rapid thermal stress-annealing step at 950°C. Although MICS was used to demonstrate several integrated microsystems, subsequent research at Sandia National Laboratories showed that it is not sufficiently robust for manufacturing [21]. Problems remain due to high and variable contact to the P diffusions after the polysilicon microstructure thermal cycles, as well as delaminations of tungsten metal lines.

Another approach that overcomes the planarity issues of building the MEMS before the CMOS has been developed at Sandia National Laboratories. In this approach, micromechanical devices are fabricated in a trench etched on the surface of the wafer. After these devices are complete, the trench is refilled with oxide, planarized using chemical-mechanical polishing, and sealed with a nitride membrane. The wafer with the embedded micromechanical devices is then processed using conventional CMOS processing. Additional steps are added at the end of the CMOS process in order to expose and release the embedded micromechanical devices. A cross section of this technology is shown in Figure 2-27.

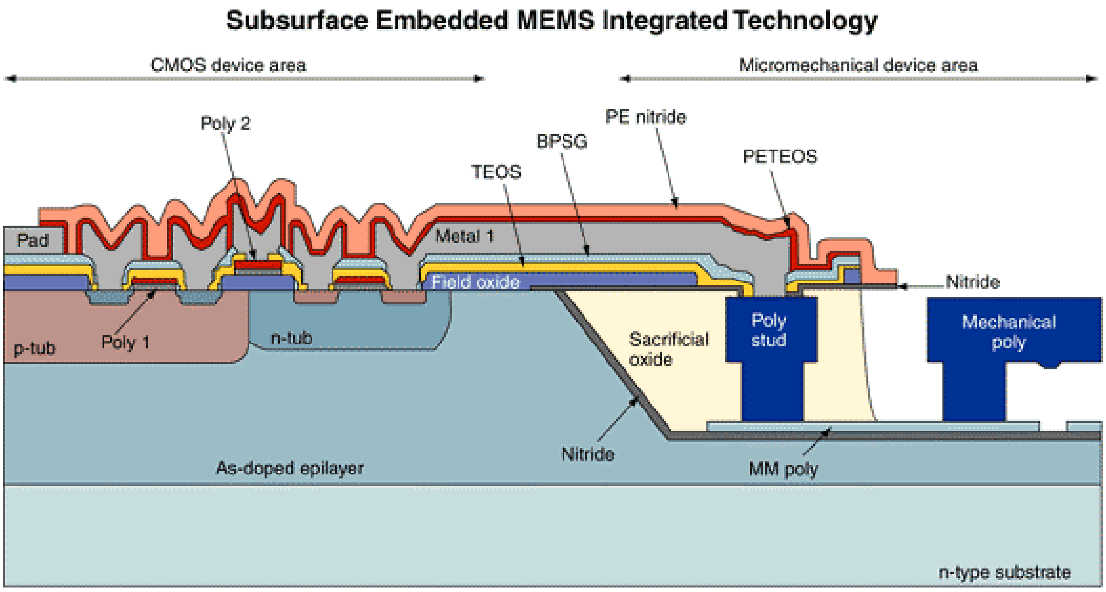


Figure 2-27: A schematic cross section of the approach to CMOS/MEMS integration [22]

Advanced CMOS processes (e.g., with multiple levels of metallization) can be used without changing the micromechanical process flow. Alternatively, a deeper wall would make feasible multiple polysilicon layers. If deep reactive ion etching (RIE) patterns are refilled with sacrificial and structural layers, then three dimensional structures can also be integrated. Using this approach, a 30μm high molded polysilicon proof mass was embedded in the wafer, prior to conventional surface micromachining. Modularity is therefore very attractive, since it enables separate development paths for the CMOS and polysilicon MEMS, which will be necessary for high performance integrated microsystems.

2.7. ALTERNATIVE MICROSYSTEM TECHNOLOGIES

In addition to bulk and surface micromachining, several academic and industrial groups have merged other MEMS processes with CMOS technologies. Recent advances in dry-etching processes have made feasible High-Aspect-Ratio Micro machining (HARM) structures embedded in the silicon wafer. These structures can easily be much thicker than LPCVD polysilicon structures and yet maintain lateral widths and gaps on the order of a few micrometers or less. For some sensor designs, the resulting blade-like suspensions are attractive for suppressing out-of-plane motion; also, the larger sense capacitors can make the interface electronics more straightforward.

Integrated processes based on silicon Reactive Ion Etching (RIE) include the SCREAM (Single-Crystal Reactive Etching and Metallization) technology from Cornell, the sealed cavity wafer bonding process from MIT and the dissolved wafer technology from the University of Michigan. The epi-poly integrated process yields thick polysilicon structures with similar aspect ratios.

Integrated technologies based on metal microstructures are also competitive with polysilicon surface micromachining. Since the deposition temperatures are much lower than for polysilicon, it is possible to achieve a modular process by completing the CMOS process before microstructure fabrication. The multi structural level digital mirror display (DMD) process is intended for display applications but could also be applied to inertial sensors.

First, we will see the LIGA technologies, and after we will explain 3 examples of microsystems technologies resulting in industrial transfers developed by LETI: SOI bulk micromachining, SOI surface micromachining and quartz bulk micromachining.

2.7.1. LIGA

LIGA (an acronym from German words for lithography, electroplating, and molding) is a micromachining technology originated in the early 1980s at the Karlsruhe Nuclear Research Center.

LIGA is one of the High Aspect Ratio Micro machining (HARM) technology.
In this technique, X-rays are used to carve out deep patterns in a resist. These patterns are then electroplated to form the desired structure. After the resist has been removed, tiny 3D metallic structures result, as shown on the right of the Figure 2-28. Further, the resulting metallic structure can be used as a mold insert for precision plastic injection molding. Because of the nature of the X-ray resist, these structures can have heights ranging from microns to centimetres. Consequently, structures (e.g. gears) having high-aspect ratios and being much more rugged than those produced by surface micromachining can be fabricated.

For many micromachine applications, a sacrificial oxide layer is added between the substrate and the plating base. This layer can be removed (undercut) to make the structure moveable. It is possible to make structures that are partly anchored to the substrate and partly free by patterning the sacrificial oxide layer before the plating base is deposited.

Because of the patterning technique employed by LIGA, structures with a wide range of materials can be fabricated. These structures can have horizontal tolerances of about 0.3 mm and vertical dimensions from microns to centimetres. The disadvantage of this process is the incredibly high start-up costs.The actual equipment can cost in excess of $35 million. [23]

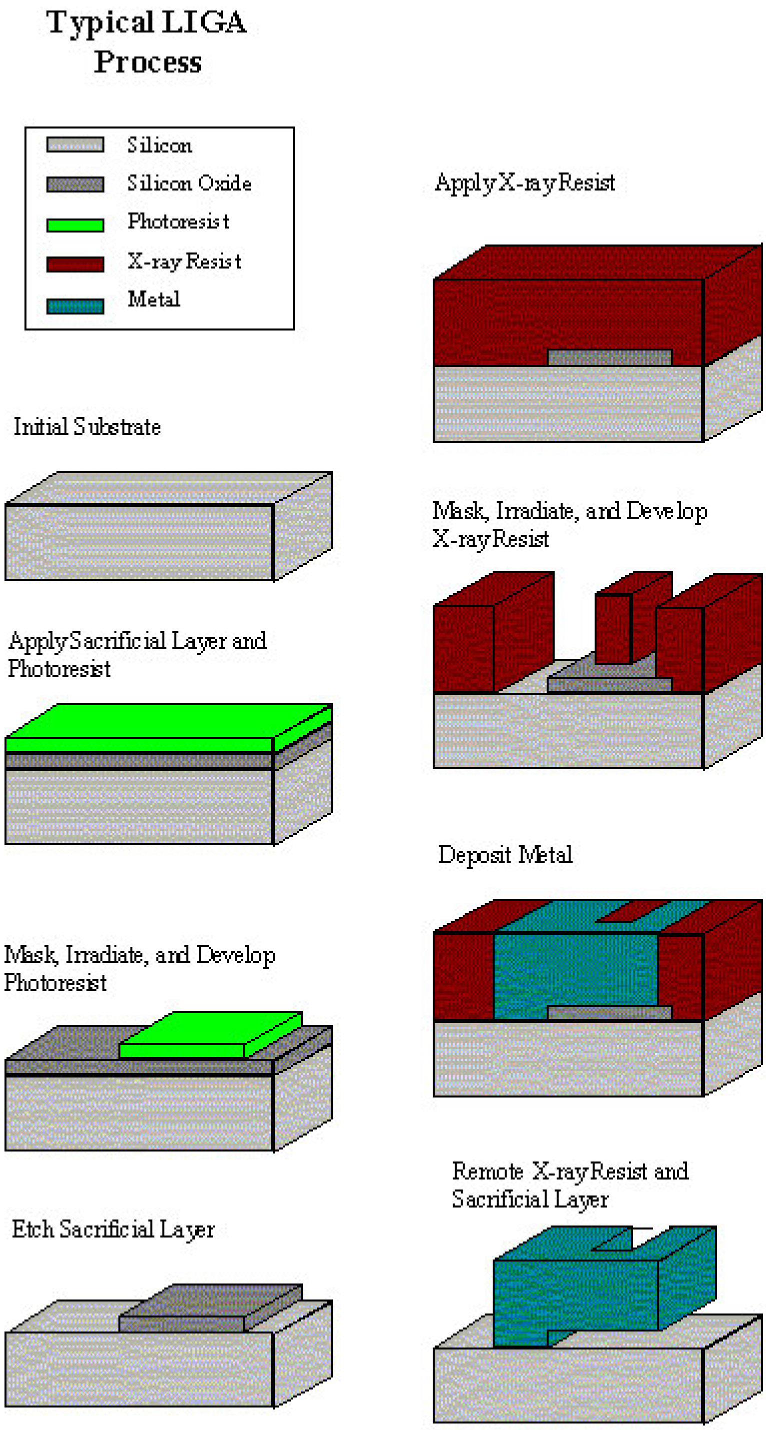


Figure 2-28: Typical LIGA process [23]

The LIGA processing steps are the following ones:

- X-rays from a synchrotron are incident on a mask patterned with high Z absorbers. X-rays are used to expose a pattern in PMMA (polymethylmethacrylate), normally supported in a metallized substrate.
- The PMMA is chemically developed to create a high aspect ratio, parallel wall mold.
- A metal or alloy is electroplated in the PMMA mold to create a metal micropart.
- The PMMA is dissolved leaving a three dimensional metal micropart. Individual microparts can be separated from the base plate if desired.

2.7.1.1. Example: acceleration sensor

However, most of the previous acceleration sensors are manufactured as a one-dimensional element. Where it required measuring three-dimensional acceleration; a group of three of such sensors would be mounted onto a suitable support using special and expensive assembly technique. The achievable mechanical precision and the grade of miniaturisation are, hence, limited. Another disadvantage of this solution is the relatively dense wire connections, which in some applications even falsify the sensor signal.

A novel three-dimensional acceleration sensor has been fabricated by combining the low cost UV LIGA surface microstructuring process with the sacrificial layer technique. [24] It enables the 3D acceleration sensor chip to be manufactured from a three-layer system. The first layer serves as an electroplating base for galvanic deposition of the sensor structure. The second layer is a sacrificial layer, which is used to help generating movable structure. The third layer constitutes the actual sensor material, which is grown electromechanically up to a height of several tens of micrometers within a patterned photoresist mould. This fabrication involves only few standard, easy manageable and CMOS-compatible processings, like UV-lithography, galvano-forming and wet etching.

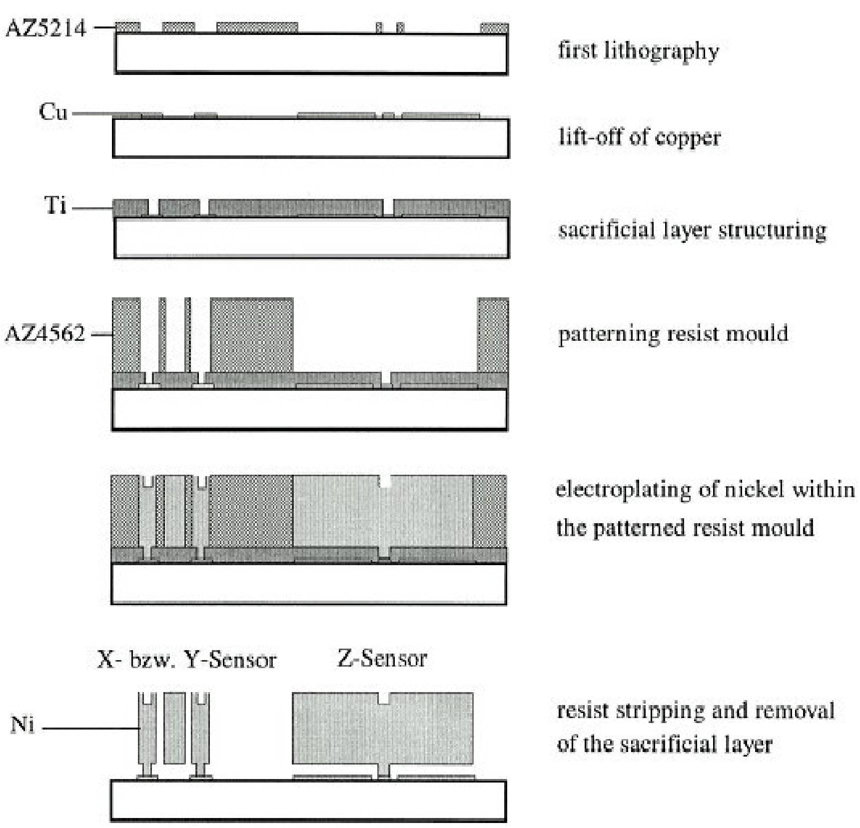
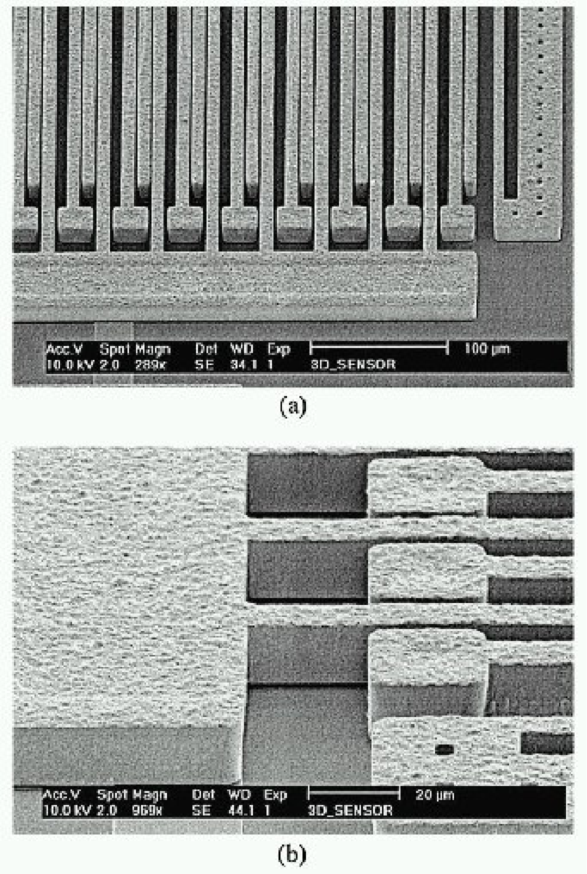


Fig. 4. Relevant steps in the fabrication of the 3D acceleration sensor.

Figure 2-29: Relevant steps in the fabrication of the 3D acceleration sensor

The fabrication steps are illustrated in Figure 2-29, in which the structures on the left side of the substrate represent the laterally sensitive accelerometer while the structures on the right side represent the vertically sensitive accelerometer.



(a)

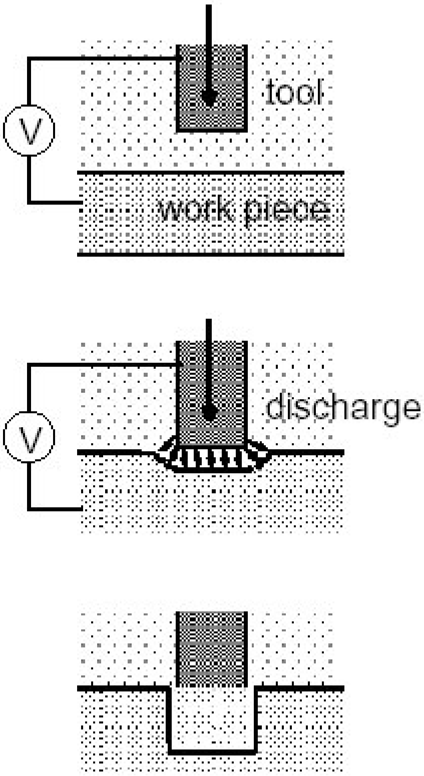
(b)

Figure 2-30: The SEM photographs of some details of the 3D acceleration sensor: differential-capacitor configuration (a) and free-standing structures (b)

2.7.2. Electro discharge Machining

Electro Discharge Machining (EDM) is a widely used method for shaping conductive materials. EDM removes material by creating controlled sparks between a shaped electrode and an electrically conductive work piece. EDM moves a fine wire, which is used as the electrode, through a sheet of part material and moves it along a programmed path.

With this technique, excellent surface finish can be obtained but the technique is limited to parts with straight sidewalls.



Here is the principle of electro-discharge machining:

✓ The shaped electrode tool moves toward the electrically conductive work piece.

✓ As part of the material is eroded, the electrode is slowly lowered into the work piece.
✓ The motion goes on until the resulting cavity has the inverse shape of the electrode.

✓ Dielectric fluid is then flushed into the gap between the electrode and work piece to remove small particles created by the process and to avoid excessive oxidation of the part surface and the electrode.

Figure 2-31: Principle of Electro Discharge Machining (EDM)

The picture below shows a cylindrical electrode of 30µm in diameter used to build microstructures.

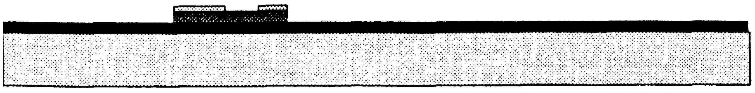
Figure 2-32: Cylindrical electrode (Ø 30µm) used in EDM [26]

2.7.3. SOI Bulk micromachining

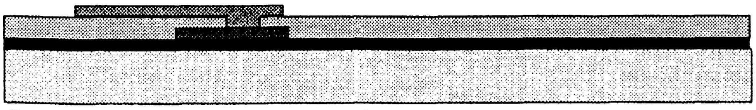
SOI bulk micromachining is based on silicon anisotropic bulk chemical etching for the realisation of mechanical structures. The SOI structure is used in this case to perform piezoresistive gauges, then allowing the achievement of very sensitive devices. For complex structures, the silicon structures, the silicon wafer can be bonded to another wafer, pyrex glass or silicon. An example of realization is a high temperature pressure sensor. The technology has been transferred to LETI's industrial partner, THALES AVIONICS and TRONIC'S MICROSYSTEMS.

Piezo resistive silicon strain gauges have been widely used as detection elements for pressure or acceleration sensors for at least twenty years. Their main characteristics are a high sensitivity, a high mechanical stability due to the single crystal structure, a small size and a low cost. Conventional methods for manufacturing these gauges are diffusion or ion implantation. Electrical insulations from each other and from the substrate are realized by reverse junction. This insulation mode has two main drawbacks: limited operating temperature range, lower than 125°C and high noise reducing the dynamic range. A SOI solution avoids these drawbacks, thanks to its perfect insulation allowing low noise sensors with an operational temperature range up to 300°C.

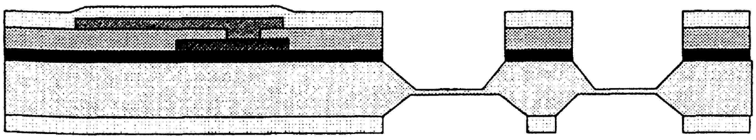
The basic technology can be demonstrated on a SOI piezoresistive pressure sensor.[25]



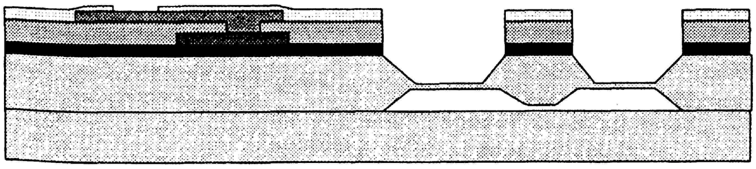
SOI wafer - Gauge & contact implantation - Gauges definition



Gauge passivation - Contact holes - Metal



Etching masks definition - TMAH etching



Masks etching - Anodic bonding

Figure 2-33: Main process steps for piezoresistive SOI bulk technology (up) and structure of the piezoresistive pressure sensor (down) [25]

2.7.4. SOI surface micromachining

SOI surface micromachining is based on plasma anisotropic etching of an epitaxial silicon layer followed by sacrificial and selective chemical etching of the buried silicon oxide. The technology had been transferred to the company ELA and to TRONIC'S MICROSYSTEMS [25.]

Mass production for silicon sensors needs cheaper sensors. Among the different possibilities, the chip area reduction is absolutely necessary and surface micromachining seems to be the key technology to manufacture low cost miniaturised silicon sensors. The SOI micromachining has the followings advantages: substrate industrially available (SIMOX or UNIBOND); CMOS compatibility; single crystalline silicon surface layer; freedom on the surface structure thickness by epitaxial process.

We can see the use of this technology in a surface micromachine accelerometer. We know that industrial and automotive markets need low cost accelerometers that are mainly surface micromachined. For a reasonable photolithography resolution (1μm) the only way to satisfy this need is to use thicker silicon films. This requirement is more feasible by epitaxy on SOI substrate than by polysilicon deposition.

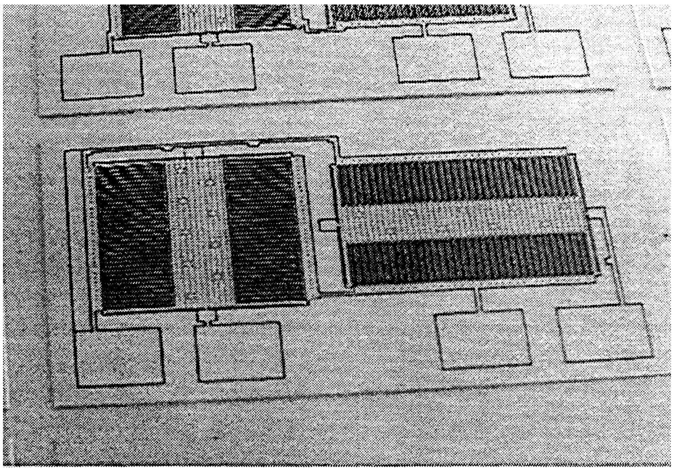


Figure 2-34: SEM view of a bi-axis accelerometer on silicon wafer [25]

2.8. MICROSYSTEMS FOR SPACE

2.8.1. Introduction

The advent of devices and systems generally regarded as Micro and Nano Technology (MNT) is to be addressed by space system designers. Space systems can benefit from the features of MNT in four main areas :

- Increased performance/mass ratio, for instance by integration of a complete functionality of a spacecraft through MNT devices.
- Lower in-orbit delivery cost per function, from launch mass (payload mass) reduction mainly, and also from batch production[3].
- High degree of miniaturisation (cause for the two direct advantages above).
- Improved reliability and robustness as there are usually no bearings - movement usually via flexures

Currently the main development prospects are for integrated micro-scale devices generally regarded in Europe as Micro System Technology (MST). At the implementation and development level, three ways of introducing MST in space systems can be contemplated:

- Component Level MST substitution:
  When sufficient confidence in use of MST for space can be gained by the customers, MST can be introduced gradually by including MEMS components into near term spacecraft. An example may be to use MEMS RF switches in RF payloads
- *MST-based complete spacecraft subsystems:*
  Entire subsystems or equipment can be replaced or improved gradually using relatively integrated devices, primarily in AOCS and sensing subsystems.
- *Integrated MST for space missions design :*
  MST is not only about making things smaller. It is believed that MST and Nanotechnology can enable new missions or improve the current ones by considering new concepts for system level spacecraft and mission design, using concepts such as the completely integrated Nanosatellite composed almost entirely of Micro devices and able to perform significant tasks.

The development of microdevices for use in space systems builds on the very substantial research and industrial work performed in terrestrial applications. Microtechnology is used commercially in several fields and has a market of several billions Euros [Force, 2002]. It is based on microfabrication techniques [Madou, 2002] derived from silicon etching processes (such as CMOS). MST (Micro *System* Technology) in turn seeks to integrate microdevices so produced with the associated electronics and with other microdevices. This concept can provide highly functional, compact and independent microsystems [Maluf, 2000]. In Figure 2-35 is shown a typical surface microengineering process.

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[3] The term “mass production” is ambiguous when talking about MNT for space. The batch size for which space systems are considered produced in series, is usually considered by MNT manufacturers as very small. Yet the situation will probably improve with respect to the current situation where any unit used in satellite technology is seldom produced twice identical, despite efforts of standardisation. Also the possibility will open for satellite assemblers to share initial production set-up costs with other industrial domains.

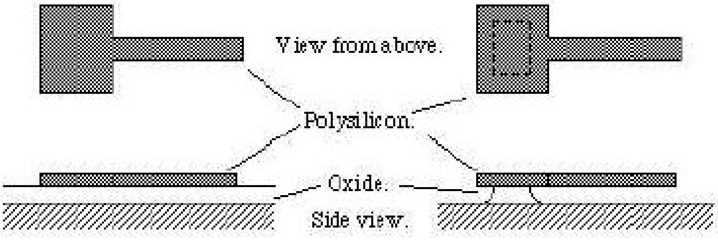

Figure 2-35 - Principle of surface micro-machining. Image Source Danny Banks

The current MST development model includes two extremes. On the one hand, there are a few very large foundries creating mass market products by developing their own facilities (such as Analog Devices[4]). On the other hand there are several SMEs and academic research centres able to develop prototypes (such as LAAS[5] or RAL[6]). Space applications are only a small part of this development, and are not considered a priority by MST and microelectronics developers [Howes, 2003]. Still, substantial work is taking place in the area of microsensors, microactuators, and integrated microsystems for space.

2.8.2. Sensors

The largest research in space microsensors is in the development of a so-called Inertial Measurement Unit (IMU), including rate sensors and accelerators. COTS MST "gyros[7]" and accelerometers are available [Stein, 2001] with increasing performances [Bernstein, 2003]. It is worth mentioning that at present, performances of micro-fabricated rate sensors are much below usual requirements for fine attitude pointing of spacecraft, specifically in terms of long-term bias.

MST-based magnetometer prototypes exist using different technologies such as fluxgate or AMR [Schneider, 1998; Viera, 2003]. They are accurate to a few nanoTeslas. Some can be machined using a CMOS-compatible process (see *Figure 2-36*).

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[4] http://www.analog.com

[5] http://www.laas.fr

[6] http://www.cmf.rl.ac.uk

[7] MST rate sensors use technologies based on measuring the change in vibrating structures to recover the rotation rate. They are not strictly gyroscopes but the term is used (although incorrectly) for rate sensors in general.

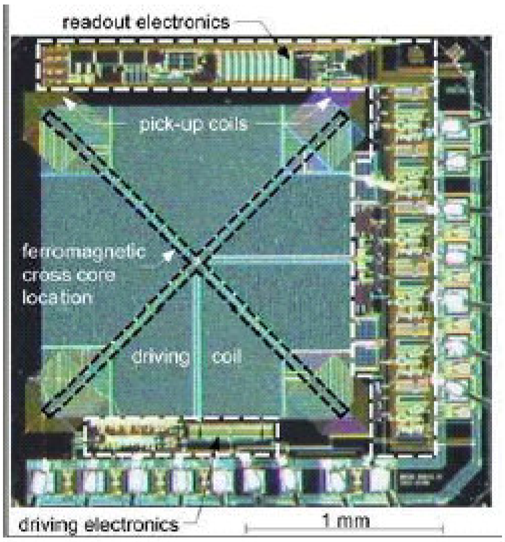

Figure 2-36 - A micromachined self-assembling magnetometer [7]. Image source EPFL

Some mechanical sensors are commercially, available such as strain gauges, used also in silicon pressure sensors which are a mainstream application of MST[8]. Other microsensors used in space systems include for instance nanotips used for mass spectrometers ion guns [Kent, 2000], AFM onboard planetary probes [Gautsch, 2000], and environmental sensors [Lecuyot, A. and Snelling, M. 2003]. There are also efforts in miniaturisation of sensor arrays for microcameras and Earth or Star sensors [Ogiers, 2000] which are not usually considered to be MST.

2.8.3. Actuators and propulsion

Research on actuators for space systems is centered around RF switches for microwave systems, optical micro-mirrors, and propulsion systems. Optical micro-mirrors are being developed in Europe for possible use on future space telescopes [Zamkotsian, 2002]. There are other applications such as micro-optics [Bright, 1999] and lasers in the longer term. In these, operation of basic optical functions has been demonstrated.

Micro-propulsion systems receive a lot of attention in the space community [Larangot, B. and Rossi, C. 2002]. There is research going on in the field on solid microthrusters or ``digital propulsion" (see Figure 2-37). [Larangot, B. and Rossi, C. 2002] provide a good review of micropropulsion which is summarised below and where the specific references can be found.

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[8] See for instance http://www.microstrain.com .

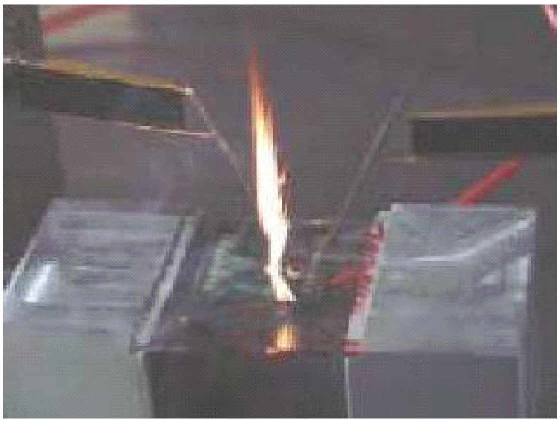


Figure 2-37 - Solid microthruster firing test. Image Source LAAS

For cold gas system the use of piezoelectric valves enables the reduction of a commercial system in size and mass. Solid micropropulsion is also a significant area of research where several designs have been successfully tested, including flight demonstration (see section 2.9.2).

For monopropellant systems a MEMS-based hydrazine thruster has been developed which has adequate performance, but an even more performing system is in development. There has also been some research into bi-propellant engines, which is less advanced than monopropellant so far. Finally some designs of the various electric propulsion systems have been tentatively miniaturised. In general, and in particular for FEEP thrusters, the difficulty comes from the high level of power and thus the bulky electronics necessary to produce the thrust, even with a micro-thruster. On Table 2-5 is shown a summary of the capacities of the systems described above (from work by [Larangot, B. and Rossi, C. 2002]).

System	*Thrust (mN)*	*Isp (s)*
Cold Gas	0.1-10	45
Digital Solid Propellant	20	-
Liquid Monopropellant	0.01-1	145
Liquid Bipropellant	1000	300

Table 2-5 - Capacities of currently developed micropropulsion systems from [Larangot, B. and Rossi, C. 2002]

2.8.4. Other subsystems

Other subsystems of a spacecraft are being investigated for miniaturisation. Long-term systems using radioactive decay as power sources are studied, which are, however, in early stages of development [Lal, 2003]. Other power generation and storage methods, such as power harvesting are also currently under investigation. One can also make use of micromachined antennas to provide small communication systems [De Maagt, 2001]. Finally, thermal microsystems are also investigated [Larsson, 2000].

2.9. COST OF MST

One of the often stated benefits of MST is the cost saving that can be realised by reducing launch mass and by the utilisation of mass production methods associated with the semiconductor industry.

It is certainly true that the launch is an expensive element of the overall space mission cost. Large launch vehicles specialising in boosting 3 to 5 tonne satellites into geostationary orbit typically charge around $30k per kilogramme so even a modest mass saving is worth pursuing. Replacing a 30 kg AOCS subsystem with a 1 kg MST AOCS will save around $1M. A satellite owner would then be able to take the saving or trade it for an increased payload capability.

Against a possibility of saving millions of dollars the cost of MST devices is probably not an issue at present. They can be as expensive as the equipment they replace but as long as performance is matched, they will be attractive. However, there is continuous pressure to reduce launch costs and more capable, easy to use and reusable systems are being developed that promise to reduce this cost by an order of magnitude. Against these future costs it is vital that MST is very cheap otherwise the difficulty of it becoming widely accepted by the space community as a reliable replacement of tried and tested technology will be overwhelming.

2.9.1. Packaging and Integration

Making a micro device is only the first step in the process of applying it to space. Despite the numbers of devices that have been made and reported on, many of them remain in the laboratory. They would not survive the handling involved in integrating them into a spacecraft. Devices have to be packaged in such a way as to permit them to be handled and to allow access to the electrical or other interfaces necessary to make them work.

Many devices will only function in a vacuum so the device has to be encapsulated under vacuum and the case must be sealed. The packaging material has to be compatible with the material from which the micro device is made otherwise it will not be possible to bond the device into the packaging. Several types of device need not only electrical interfaces but also interfaces to plumbing for gas or liquid.

The particular problems associated with packaging MST is noted by many authors. They conclude that the cost of packaging a piece of MST can be as expensive as the MST device itself and by the time the interfaces to the macro world are incorporated the MST device can be quite large and its performance compromised. It may not always be sensible to consider packaging a micro system in one package as:

a. Various components will have to be distributed (eg AOCS will want sensors at various places on the outside of the structure) and

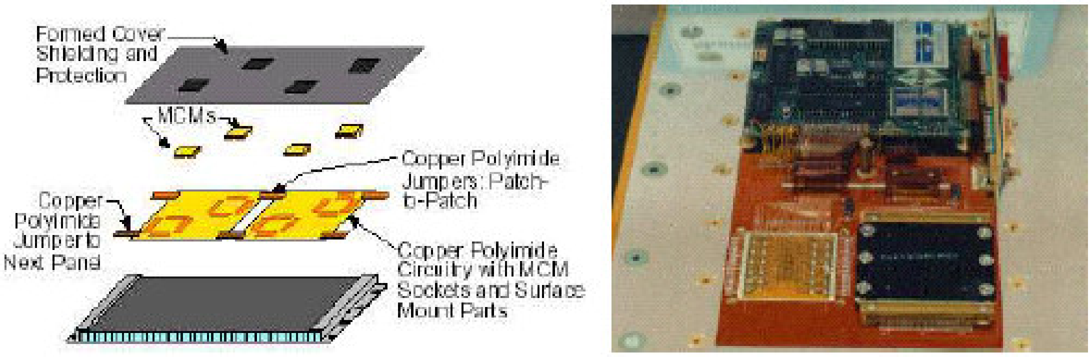
b. The packaging requirements of the various components will be different (eg. CMOS electronics and bi-polar sensors).

Also, silicon is a good conductor of heat so the design and packaging of sensors that require to be thermally isolated can be a challenge.

The integration of MST in space systems creates two challenges; validation and qualification on one hand, and integration on the other. Qualification means that the failure mechanisms of MST have to be understood in detail [Schmidt, 2003]. Equally, the space community has initiated qualification programs for specific devices [Barthe, 2003]. As for integration, there are several options that have been studied by industry [Lecuyot, A. and Snelling, M. 2003, and Eckersley, S. 2004]. Initial implementations of microsystems is done with hybrid integration. Prototypes have been developed and flown for this level of integration [Manhart, S. and Melf, M. 2000]. However for industrial uses in the middle term \gloss{MCM}-level integration is necessary.

The full potential of microsystems can only be realised when integration levels of the SOAC (System-On-A-Chip) can be reached, which are currently in early research phases [Lecuyot, A. and Snelling, M. 2003]. The key issue with SOAC is the compatibility of different processes used to make different parts of the system. JPL have prototyped such a process based on a space-compatible silicon process [JPL, 1999], but no operational applications exist yet.

Packaging of microsystems is tightly related with integration for lower-level packaging (see above). For higher-level packaging (i.e. at box level) concepts such as multifunctional structures [Barnett, M. and Rawal, S. 1999] are necessary (see Figure 2-38). This enables to provide packaging with structural functions, or structures with specific functions, such as harness routing or electrical connections. This is also a key technology for nanosatellite integration.



(a) Principle (b) Constructions

Figure 2-38 - Multifunctional structure on Deep Space 1. Source JPL/Lockheed Martin.

EADS is developing such an micro package to demonstrate advanced packaging of COTS Microsystems, inside a multi-functional structure [Eckersley, S., Schalk, J. and Koppenhagen, K. 2004]. This micro package include several sensors, a microcontroller, a RF- link and a power supply unit. All these components will be integrated into a ceramic LTCC housing with a size of approx. just 25x25x20mm^3. The sensors are manufactured in MEMS technology to develop devices with small size, low power consumption, and comparatively high measurement performance. The signal amplifying and conditioning is also included on chip, which saves computing resources, weight and energy. The principle suitability of the MEMS components for space applications has been demonstrated by several experiments.

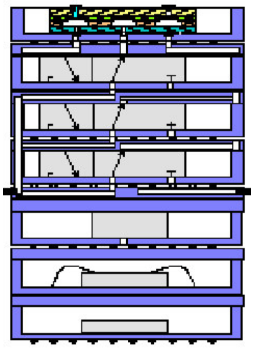


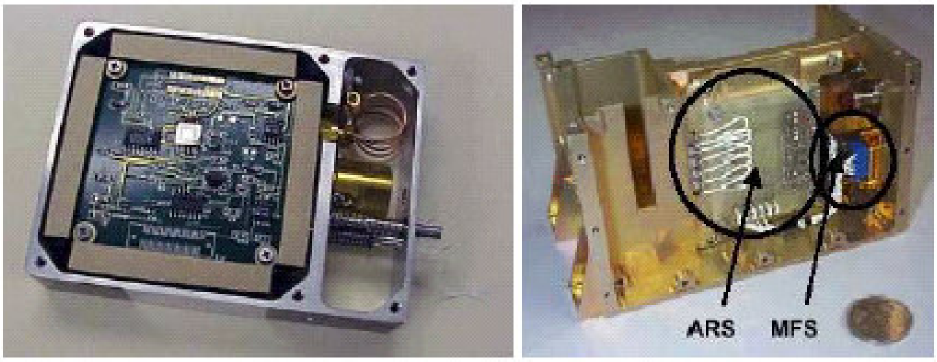
Figure 2-39 Advanced 3D ceramic packaging is used for the EADS micropack

Another innovation is the use of LTCC material for the housing. This ceramic material is chemically inert against the most acids, and other substances. This makes it applicable for nearly all applications with harsh environments. The ceramic LTCC material is also applicable for the development of nano satellites. The low temperature coefficient ensure low mechanical stresses over the whole temperature range and a relatively high heat conductivity for a simple thermal management. Further, ceramic materials are ideally suited in a vacuum, because they have no outgassing effects.

2.9.2. Flight experiments

The vast majority of the developments mentioned above have been tested on the ground. For space systems qualification is vital, in particular through flight validation. In this respect, only a limited number of MST devices have flown.

The Aerospace corporation[9] has flown microthruster experiments on the Shuttle rack [Helvajian, 1999], and has flown a pair of so-called ``PicoSats" that include genuine microtechnology [Aerospace, 2000]. In Europe, EADS Astrium has flown an MST-based attitude sensing package [Manhart, S. and Melf, M. 2000]. These flights experiments performed well and are shown in Figure 2-40.



(a) A PicoSat from Aerospace Corporation (b) The MTS-AOMS from EADS Astrium

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[9] http://www.aero.org

Figure 2-40 - MST-Based Flight Experiments. Both have operated successfully in flight.

The MTS-AOMS (Micro- Tech Sensor for Altitude and Orbit Measuring System) comprised of three COTS micro system technology sensors. A CMOS-APS from IMEC, a micro machined angular rate sensor from Bosch and a dual- axis fluxgate magnetometer from IPS. These components were integrated into the Italian micro satellite, MITA and launched.

Over a period of one year, the system performed well, until the satellite was switched off. It was the longest period of operational micro system technology in space and demonstrated the usability of MEMS for space applications.

2.9.3. Transition out of the Laboratory

For MST to become widely available and used in the space industry requires that it moves out of the laboratory and is produced in significant numbers by processes that can be assessed for reliability and reproducibility. Only in this way will the technology gain the credibility that will make it acceptable in the commercial market.

Presently many devices with potential space application are made almost by hand, one at a time. Each device has significantly different performance and it is luck that a device is made that performs well. Many of the devices that have been noted in this survey fall into this category. The papers and articles describe the best of a batch and there is no indication of the reproducability of the manufacturing technique.

Whilst the survey notes that there are many devices that have been produced and shown to work, there is no guarantee that any more could be made if an order were placed.

2.9.4. Radiation

The radiation environment found in space is harsh and is a major design driver for all hardware, not just silicon based devices. Energetic particles or photons passing through matter lose energy through a variety of interactions and scattering mechanisms. Of particular concern for electronics and hence MST is the resultant ionisation and atomic displacement.

Above a threshold energy, atoms can be displaced out of position in a crystal lattice, leaving defects, which will degrade the electrical properties of a (p-n) junction. The ionisation process generates electron-hole pairs, which contribute to the noise of a device. Very energetic events (cosmic ray induced) can cause a sufficiently high pulse of noise as to cause a change in logic state (a single event upset).

The effects are complex, cause transient degradation or long term damage and are critically dependent upon the manufacture process and choice of materials.
MST devices that rely on small changes in capacitance caused by the relative motion of some parts (for example many designs of accelerometers and gyros) are particularly sensitive to radiation. The instantaneous charge distribution caused by the passage of ionising radiation will cause noise and mask the small effects being looked for.

The radiation environment in Earth orbit is well understood. It depends upon latitude, altitude and the point in the solar cycle. It mainly results from energetic electrons and protons and is modelled by AE8 (for electrons) and AP8 (for protons) - see ESA ECSS documentation for an extensive description of radiation effects and design considerations. Fluxes in the order of 10E8 energetic electrons and protons /cm^2/sec can be expected. Total dose rates can range from 10E6 rads/year (LEO, solar minimum) to 10E8 rads/year (GEO, solar maximum). A couple of millimetres of aluminium shielding will reduce the dose rate by two orders of magnitude.

The harshest radiation environment would be that in the vicinity around Europa (a proposed case study environment) , which is around 1.5 Mega rads/month. Missions planned for this destination, may include MEMS, which would have to tolerate such high radiation doses.

2.9.5. Patents

There are many patents issued in the field of MST, particularly for the manufacturing processes. They are often not enforced but if this technology proves to be commercially very attractive then we can expect others to check what they have patented and chase infringements. Funding to support the application for patents on developments arising out of this MST work should be made available.

2.10. SPACECRAFT CONCEPTS WITH MST

In recent years, the advent of microelectronic devices, microelectromechanical systems (MEMS), and the rapid evolution of micromachining technologies, have generated fresh attention from the space community in the mission capabilities of "next-generation" micro and nanospacecraft, which can outperform the simple radio transmitters and Geiger counters installed on their early grandparents by many orders of magnitude.

The present vision is one of swarms of micro and nanospacecraft circling Earth, the Sun or other planets in the Solar System, performing critical and highly complex tasks, interacting with each other and with the ground or space operators, and with a high degree of autonomous control capability. advanced micro and nanospacecraft with distributed functionality are envisioned to take the place of more massive and expensive conventional spacecraft, with the additional advantage of increased survivability and flexibility. In this scenario, very small satellites (<30 kg), alone or in constellations, have gained a strong momentum and have been proposed for a number of missions both in the commercial and in the scientific application segment.

Very small satellites can significantly reduce mission costs as associated launch costs are dependant to a large degree on the spacecraft mass. As launch costs contribute, as already mentioned, to roughly 30% of mission costs, reducing the spacecraft mass will result in a decrease of the mission costs.

The classification of the spacecraft is important in determining applicability of MNT in various spacecraft system designs. Spacecraft below 100kg can fall within several frequently-used categories depending on their mass range. The spacecraft classification used by the US Air Force Research Laboratory (AFRL) and in Europe, defines different vehicle categories according to the launch mass as follows:

- 100-1000 kg minispacecraft
- 10-100 kg microspacecraft

- 1-10 kg nanospacecraft
- < 1 kg picospacecraft

Interestingly, M. Micci, A. D Ketsdever in 'Micropropulsion for small spacecraft' have categorised spacecraft slightly differently depending on their mass range (see Table 2-6), for propulsion architecture. This must be taken into account as the requirements regarding system integration and miniaturisation will be different in each of the categories. Although this table was prepared for propulsion architecture, it could equally be applicable to other spacecraft subsystems, and gives us an idea of the type of integration and fabrication that might be expected for different mass classes of spacecraft.

Spacecraft type	Mass (kg)	Spacecraft Power (W)	Dimensions (length) m	Comments on Subsystem Architecture
Microspacecraft - USAF and European definition	10-100	10-100	0.5-1.1	Use of both miniature conventional and standard components
Class I Micro spacecraft (Nanosat)	5-10	5-10	0.2-0.5	Use of miniature conventional components possibly MEMS or microfabricated.
Class II Micro spacecraft (Nanosat)	1-5	1-5	0.1-0.2	MEMS or microfabricated components. Possible subsystems-on-a chip
Class III Micro spacecraft 'Picosat'	<1	<1	<0.1	All MEMS or microfabricated. Very high level of integration.

Table 2-6: Micro and Nanospacecraft classifications

Other definitions for very small satellites have been used:

- 1-0.1kg picospacecraft
- <0.1kg Femtosatellites ('spacecraft on-a-chip' idea)

MEMS components can lead to smaller Micro and Nano satellites. The concept of the Nanosatellite is usually[10] accepted to mean satellites in the range of less than 1 to less than 10 kg [Helvajian, 1999]. On Table 2-7 are shown a few representative concepts for current nanosatellite projects and their relevance to MST. Note the differing levels of MST usage.

Project / Concept	*Organisation*	*Mass*	*MST*	*Status*
OPAL	Stanford Uni	13.6 kg	None	Successful flight
SNAP-1	SSTL	8 kg	None	Partially Successful flight
Nanospace 1	Uppsalla Uni	< 1 kg	Some	In development
PicoSat	Aerospace Corp.	< 1 kg	Mostly	One successful flight
WaferSat	Aerospace Corp.	< 1 kg	All	Concept Only

Table 2-7 - Some representative Nanosatellite projects

Future nanosatellite concepts are envisaged to be much more advanced than nanosatellites of today. As well as using MNT, future nanosatellites could display advanced packaging techniques with substantial modularity (i.e. 'plug and play' modules). Also advanced integration with in-built instrumentation, such as magnetometers, into the structure will also play a part.

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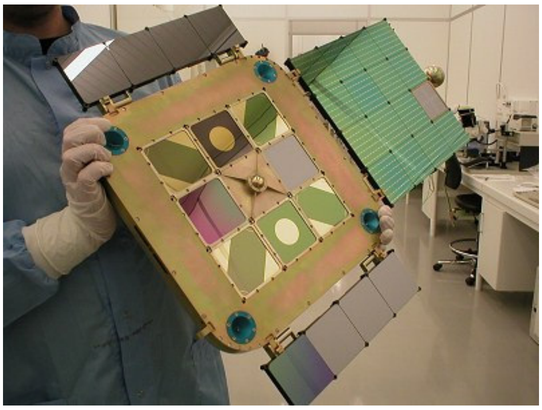
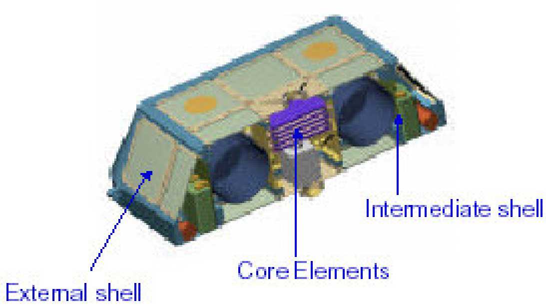
[10] Although there is no strict classification.

NanoSpace 1 (Angestrom Centre Sweden) will be the first nanosatellite based on extensive use of micro/nano tech and multi-functional Microsystems. 2006 launch, currently in Phase A. The equivalent is 50% of one MMS module if filled with naked dies. 3 MMS Modules includes also discrete components, resistors, capacitors, etc.

- Total weight: ~ 120g
- Total size: 74x74x22 mm
- (NanoSpace Module Equivalent)
- Reduction: 70 times in weight, 120 times in volume compared to CON unit of SMART-1



Nanospace 1



Cross section of Nanospace 1

In the longer term, further miniaturisation of satellites will take place. The MEMS components can be integrated into new satellite concepts, in order to get very small nano satellites. New technologies like 'system on a chip' and structure integrated components/circuits will open up new possibilities for scaling down the size. For instance, resistors can be implemented using thick film metallisation and laser trimming. The active components like amplifiers and microcontrollers will be integrated on die level, i.e. without the need for chip housing. The electrical connections will be carried out with wire bonding or directly on the metallisation.

The laminating of components into the carrier material will lead to 3- dimensionally stacked muli-layer modules. In fact, the technology of the manufacturing of these 3- dimensional multilayer is also an important part of the micro system technology. The whole multilayer including sensors, signal conditioning, controlling and communication, can be seen as a new micro system altogether. These micro packs will have a range of advantages, such as; small size, modularity, robustness, low cost, etc, which are beneficial for space applications. EADS is currently developing such a concept for space applications (see *Figure 2-41*) [Eckersley, S., Schalk, J. and Koppenhagen, K. 2004].

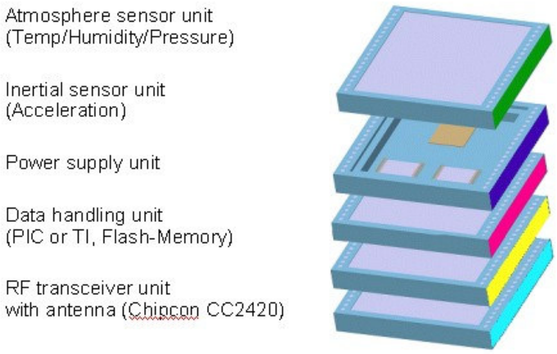


Figure 2-41: Discrete LTCC Modules in the 2004 micropack

Furthermore, multiple micro packs can be combined to operate in swarms, which can open up new functionality. For instance it is possible to share resources or measurement functions. A data fusion will ensure a treatment like one common system. Additionally, reliability management is very easy to be implemented. Faulty micro systems can have their functionality replaced by other healthy micro systems. This ensures a safe and stable operation during the whole mission.

The most advanced concept, is the so-called “WaferSat” [Helvajian, 1999] or silicon satellite (see Figure 2-42). This is a fully functional satellite, which is about 10 cm in size. The same organisation behind this concept has also flown so-called picosatellite demonstrator of MST-based satellites [Aerospace, 2000]. MNT is a converging process. Microsystems reduce subsystems, and advanced integration reduces bus size (harness & structure). The concept of functional Nanosatellite (<10 kg) is now realistic. This will ultimately lead to the concept of a Silicon satellite. Nanosats can be mass produced, so are dependable and usable in clusters (formation flying). Current satellites contain thousands of individual components. Most components are “dumb” (inert). Electronic microfabrication techniques will produce smaller, smarter, and less costly components in a batch mode. Future nanosatellites will include:

- **Highly-integrated designs**
    - More functional elements, fewer piece-parts
    - Integrated diagnostics, self-test, and reconfiguration
    - “Silicon satellites”; grams-to-kilograms in mass
- **Batch or assembly-line fabrication in large lots (>100)**
    - Virtual satellites, e.g., km-scale sparse aperture arrays
    - Disposable satellites, e.g., satellite inspectors
    - Dense constellations for continuous Earth coverage

- **“Two-dimensional” satellites**
    - Large aperture/weight ratios, e.g., TechSat-21

Additionally the Silicon itself is multifunctional and will serve as:
- Structure,
- Radiation shield,
- Thermal control,
- Optical material,
- MEMS substrate,

- Electronic substrate

However some basic problems remain due to small sizes and the use of silicon, such as small antenna size, radiation and limited shielding volume, low power generation, thermal cycling due to low mass etc.

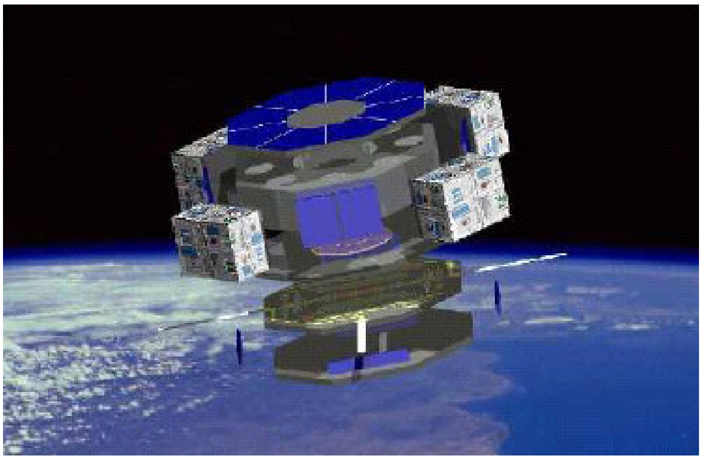


Figure 2-42 - The Wafer Satellite concept from Aerospace corporation

Other non-satellite spacecraft concepts can also benefit from using MEMS in the same way as micro and nanosatellites. This includes:

- planetary aerobots/air vehicles
- planetary descent microprobes
- solar sails
- penetrators
- autonomous robotic planetary explorers

All of the above applications are completely different in complexity and resources. For each specific application, a programme of modification, qualification and testing (e.g. thermal and radiation) will be required for the micropack. One example mission scenario, the ESA Venus Entry Probe Technology Reference Study, would be a particularly attractive mission opportunity for MEMS technology, as it requires an ultra-low mass aerobot for the upper atmosphere and 15 sub 100g ballast microprobes for sampling a range of altitudes.

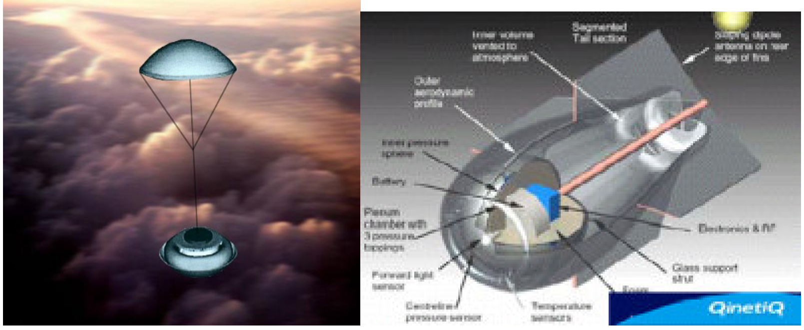


Figure 2-43 The ESA Venus Entry Probe Study – The Aerobot after deployment (right), the microprobe (left) (images courtesy of ESA)

2.11. MEMS FOR SPACE BIOMIMICRY

"Micro Technology" in itself is not biomimicry. However, it is a technology that can *enable* biomimicry, due to the incredibly low mass, power and volume characteristics. This was highlighted within Technical Note 1, where it was stated that;

'Biomimicry applied to space engineering promises the prospect of high miniaturisation, high integration and packaging efficiency, high energy efficiency, and high autonomy and robustness. Such robustness and adaptability is particularly critical in space exploration as the environments to be explored are typically unknown with unknown dynamics and variability. In particular, as space exploration missions demand greater sophistication and functionality, so the requirements for miniaturisation, autonomy, robustness, and survivability become paramount.'

High miniaturisation, high integration and packaging efficiency, high energy efficiency, robustness and survivability are all relevant to MEMS technology for space biomimicry,

Microtechnology can apply at all levels (i.e. component, subsystem and system level) and for all sub-systems (e.g. AOCS, instruments, structures etc). It is therefore a global technology which can apply to all levels of biomimicry.

As in the SOW section 2.3.1, MEMS falls under the bracket of new technologies, techniques and knowledge which can adapt identified biological principles to create new spacecraft systems or components

The main broad biological principles from TN1 that are particularly relevant to space systems, and apply to MEMS for space biomimicry

Technical Note 1 also highlighted five main broad biological principles that are particularly relevant to space systems. MEMS for space biomimicry can apply to principles 2,3 and 4, which are below in bold:

1. The principle of autonomous behaviour to minimise reliance on ground systems
2. The principle of integration of mechanics, control, software and electronic systems
3. The principle of robustness for survival under widely variable conditions
4. The principle of compliant, multi-functional structures as part of a control system
5. The principle of neurally-inspired control systems with selectionism (e.g. neural Darwinism)

2.11.1. The biomimicry fields from TN1 that are relevant to MEMS

In addition, of the following biomimcry fields from TN1, only those with 'physical' hardware apply to the use of MEMS. These are highlighted below in bold

1/ Biological modularity and pleiotropy:
2/ Biomimetic materials,

3/ Biomimetic structures, mechanisms and deployables:
4/ Biomimetic methods of propulsion:
5/ Biomimetic energy generation and storage:
6/ Immunological approaches to self-defense:
7/ Biological behaviour control and navigation:
8/ Memory - beyond behaviour control
9/ Biological learning
10/ Genetic & neural approaches to learning:
11/ Biomimetic sensors and signal transduction:
12/ High-level cognition and symbol manipulation:
13/ Hybrid Approaches to Intelligent Control:
14/ Group behaviour Control

Although MEMS can apply to future biomimetic designs at all levels (i.e. component, subsystem and system level) and for all sub-systems (e.g. AOCS, instruments, structures etc), specific references to MEMS (or related technology) were mentioned in various parts of TN1. These references are where there is a stand-out similarity between MEMS and biology, or a glaring example of where MEMS is applicable. These are shown in *Table 2-8*. However MEMS will also be useful in building larger systems (e.g. a leg), which more closely resemble biological designs than their current mechanical non-biomimetic counterpart.

2.11.2. Review of references to MEMS from TN1

Section	Subsection	Page No.	Section No.	Topic
Executive Summary	Biomimetic materials, structures and mechanisms	Page 3	0	PolyMEMS actuator (PMA)
Executive Summary	Biomimetic materials, structures and mechanisms	Page 4	0	Piezoelectrics
Executive Summary	Biomimetic sensing	Page 17	0	MEMS flow sensors
Biomimetic materials	Adaptive materials	Page 63	3.3.2.1	Composite MEMS Materials (e.g. Smart materials, sensing, actuation)
Biomimetic materials	Adaptive materials	Page 66,68,70	3.3.2.1.1	Polymer-based MEMS Actuator
Biomimetic materials	Adaptive materials	Page 78, 79	3.3.2.3	Piezoelectric (PZE) Materials, inc SAW
Biomimetic materials	Adaptive materials	Page 87	3.3.2.6	Conclusions (Polymer-based MEMS Actuator)
Biomimetic methods of propulsion	Winged Flight	Page 18	3.5.3.3	Entomopter (electrical energy for controlling MEMS devices)
Biomimetic methods of propulsion	Compliant structures in actuation control	Page 28	3.5.6	PolyMEMS actuators
Genetic and Neural approaches to learning	Adaptive Vision-based Flying Robots	Page 166	3.11.5	MEMS Gyros
Biomimetic sensors and signal transduction		Page 226	3.12	MEMS Hair Sensor
Biomimetic sensors and signal transduction	Tactile Sensing	Page 245	3.12.4	MEMS-based cantilever sensors
Biomimetic sensors and signal transduction	Tactile Sensing	Page 245/7/ 250	3.12.4.1.1	Biomimetic Flow and Contact/Bending MEMS Sensors
Biomimetic sensors and signal transduction	Chemical Sensing	Page 252	3.12.5	Piezoelectric materials, SAW (surface acoustic wave) sensors and coated micromachined cantilever-based micro-sensors

Table 2-8: Review of references to MEMS from TN1

There are extensive references to specific MEMS-based biomimetics in this text and TN1. MEMS may be seen as a technology enabler for biomimetics, most especially for miniaturised sensing, eg. hair transduction is a universal biological mechanism for a number of sensory modalities. MEMS has limited biomimetic actuation possibilities as biological actuation is generally reliant on the parallel use of muscle fibres (the biomimetic analogue being smart materials such as electroactive polymers), though MEMS-based microvilli may have uses in controlling capillary fluid flow (eg. heat pipes). Hence, MEMS-levered biomimetics is primarily in the field of miniaturised sensors, offering the possibility of distributed sensing (for instance, in multifunctional materials).

2.11.3. Applicability of MEMS to the ESA Biomimicry Technology Tree from TN2

TN2 defined an abbreviated and unfinished version of the ESA Biomimicry Technology Tree, presenting the ESA structured classification of technological areas related to biomimicry. Here we have assigned a yes/no criteria as to whether MEMS is applicable.

6100 Structures and Materials - Principle domain

6100 (Structures) - Technology Domain

Technology Sub-Domain	Technology Group	Is MEMS applicable?
6100 (Structures.1) Novel Structures	Structures that mimic novel forms found in natural structures. Examples include: Structures built by animals (for example honeycomb, webs) Load optimised structures Structures with novel topologies (for example water collection by stenocara beetle).	Yes
6100 (Structures.2) Dynamic/Adaptive Structures	Structures that exhibit an intelligent response to changing loads, either transient (dynamic response) or sustained (adaptive response).	Yes
6100 (Structures.3) Deployment, Folding and Packing	Novel bio-inspired deployment, folding and packing strategies. Examples include: Sunflower seed head packing Insect wing packing and deployment Leaf packing and deployment.	Yes

6100 (Materials)

6100 (Materials.1) Composites	Novel forms of composite materials that reproduce the composite nature of biological materials. Examples include: Fibrous composites that replicate lignin and polysaccharide phases of wood Plate and polymer composites that mimic the structure of shell.	Yes
6100 (Materials.2) Bio-Incorporated Composites	Composite materials that incorporate to some extent biological or engineered biological materials/molecules. An example is the use of genetically engineered spider silk proteins in high tensile materials.	Yes
6100 (Materials.3) Smart Materials	Materials that can exhibit an 'intelligent' response to stimulus. Such materials incorporate: Sensing technology Actuation/response technology Control mechanism. Examples include photo chromic glass, and self-healing/self-monitoring materials.	Yes

6200 Mechanisms and Processes

6200 (Mechanisms)

6200 (Mechanisms.1) Muscles and Actuators	Biomimetic reproduction of the actuation characteristics of living systems (plant hydraulic mechanisms etc.). The focus is on reproduction of the characteristics of muscle. Examples of candidate materials and mechanisms include: Electroactive polymers and ceramics Shape memory alloys McKibben artificial muscles.	Yes
6200 (Mechanisms.2) Locomotion	Reproduction of one or more aspects of locomotion in the animal kingdom. Examples include: Flight mechanisms (predominant focus is on reproduction of insect flight, particularly vortex control) Ambulation mechanisms mimicking natural walkers Undulation mechanisms. Within fluids (.e. swimming) the focus is again on vortex control. Also includes undulation on land (slivering) and within a solid material (burrowing).	Yes

6200 (Processes)

6200 (Processes.1) Novel Processes	Novel processes from natural systems, including: Cellular mechanisms (filtration, fluid and ion transport etc.)	Yes
6200 (Power.2) Thermal Management	Biologically inspired heat management and dissipation strategies. Includes both mechanisms for thermal energy retention and thermal energy dumping. Examples include: Use of capilliaried surfaces to dissipate heat (Desert fox ears) Differential temperature regulation within termite mounds.	Yes
6200 (Processes.3) Fabrication	Novel processes for the fabrication and manufacture of materials. Examples include: Deposition and mineralisation processes such as those involved in the growth of bone, shell and horn JIT manufacture, inspired by venom production in snakes.	Yes
6200 (Power.4) Power Generation and Storage	Power generation and storage technologies based upon mimicry of natural power production and storage (for example Pentads).	Yes

6300 Behaviour and Control

6300 (Behaviour)

6300 (Behaviour.1) Classical Artificial Intelligence	AI based upon the classical AI paradigm (physical symbol system hypothesis) of functional decomposition. Examples include: Dynamic programming Reverse topological sorting Expert systems.	No
6300 (Behaviour.2) Behavioural Artificial Intelligence	AI based upon the behavioural paradigm (situatedness) of task decomposition. Examples include: Study and application of animal behavioural mechanisms (animat approach). Development and design of basis behaviours and action selection mechanisms.	No
6300 (Behaviour.3) Learning Mechanisms	Biologically inspired behaviour in-situ mechanisms for behaviour modification. Examples include: Neural networks Learning classifier systems Reinforced learning.	No
6300 (Behaviour.4) Swarm Intelligence (DAI)	Distributed Artificial Intelligence control strategies based upon group and swarm mechanisms observed in nature. The central focus is on emergent properties and global problem solving behaviour. Examples include: Stigmergic behaviour Ant swarm mechanisms Shoaling and flocking behaviour Pack (small group) dynamics.	No

6300 (Control)

6300 (Control.1) Reflexive Control	Biologically inspired control mechanisms centred on reflexive (i.e. stimulus-response) control. The focus is on integration of sensor systems and actuation systems – of particular importance here is the field of neuroscience and animat control, where neuronal control structures of animals are reproduced in robotics.	No
6300 (Control.2) Rhythmic Control	Control using bio-inspired rhythmic pattern generators. Current focus is on Central Pattern Generators.	No

6400 Sensors and Communication

6400 (Sensors)

6400 (Sensors.1) Vision	Bio-inspired vision systems. Examples include: Reproduction of oculomotor function. Reproduction of insect compound vision Image processing including image recognition, edge detection etc. Integration with behaviour and control systems.	Yes
6400 (Sensors.2) Hearing	Bio-inspired auditory systems. Examples include: Reproduction of Pinna movement to optimise sound reception. Bio-inspired mechanotranducive mechanisms (e.g. artificial hairs) Echolocation. Integration with behaviour and control systems.	Yes
6400 (Sensors.3) Touch	Bio-inspired touch systems. Examples include: Mechanotransducive mechanisms (EAP/SMA based etc.) – include touch sensors for temperature Haptics for telepresence. Integration with behaviour and control systems.	Yes
6400 (Sensors.4) Taste and Smell	Bio-inspired taste and smell systems. Examples include: Biochemical signal transduction. Narrow and broad range compound detection. Integration with behaviour and control systems.	Yes

6400 (Communication)

6400 (Communication.1) Passive Group Communication	Communication mechanisms based upon instances such as pheromone deposition by ants.	No

6500 Generational Biomimicry

6500 (Generational.1) Ecological Mechanisms	Ecology inspired mechanisms. Examples include: Recycling Life support and enclosed biospheres.	No
6500 (Generational.2) Genetic Mechanisms	Genetically inspired mechanisms. The focus is on optimisation techniques. Examples include: Evolutionary Programming Genetic Algorithms Genetic Programming.	No
6500 (Generational.3) Cultural Mechanisms	Culturally inspired mechanisms. Focus is on development of culture within agent teams to improve task performance, as well as combining cultural and genetic techniques in optimisation.	No
6500 (Generational.4) Geneering/Human Alteration	The use of genetic engineering and therapeutic measures. Focus is split between: Mimicry of desirable traits of other organisms by therapeutic means (e.g. pharmacological means, or incorporation of trait specific genes into human genotypes (for example the ability to hibernate) Engineering/alteration of other organisms to improve their utility (for example nutritionally improved foods).	No

2.11.4. Biological Analogues to Spacecraft Subsystems Matrix

In TN1 we considered the nature and difficulty of such division in terms of biological modularity. Our concern was to bear in mind the application of biomimetic technology to space missions. Our perceived mapping takes the current form, which also includes a column of relevant example MEMS devices:

Table 2-9 – Biological Analogues to Spacecraft Subsystems Matrix

Spacecraft Subsystem	Relevant Biological System	Impact and Relevance of MEMS as a biological substitute
Space systems engineering	Evolution, embryonic development and cognitive psychology applied to modularity	System level knowledge of implementing MEMS into a larger system (e.g. packaging and interfaces)
Human element	Human-machine interfacing, closed loop ecology and hibernation strategies	Man-MEMS interfaces
Space environment	UV protection and oxidant tolerance	Radiation dose effects in MEMS
Propulsion system	Animal locomotion	Could be MEMS thrusters or MEMS components part of a larger structure (i.e. a leg)
Attitude control system	Animal navigation and vestibular system	e.g. MEMS gyros, accelerometers
Power system	Photosynthesis, ATP energy storage and in-situ resource utilisation (food)	MEMS batteries, turbines, generators
Thermal control system	Thermoregulation, psychrophilic and hyperthermophilic extremophile strategies	MEMS louvres, MEMS temperature sensors
Command and data system	Animal ethology, biological neural nets, central pattern generators, learning and behaviour control	N/A
Communications system	Animal communication and human language	MEMS antennae, RF switches, filters etc
Structural system	Biomimetic materials and structures	Smart/Multifunctional structures, MEMS packaging, PolyMEMS actuators (PMA)
Payloads (sensors)	Special senses, active vision, optic flow, electronic noses and tactile sensing	MEMS pressure, humidity, atmospheric sensors, electronic nose based on a micromechanical array of Si cantilevers, MEMS flow sensors
Reliability	Autonomy, self-repair, immune system	Reliability of MEMS devices

MEMS could play a role in nearly all of these standard spacecraft subsystems

2.11.5. Case studies and MEMS

The case studies in TN4 are 2 reference designs as follows:

- An Asteroid micro-penetrator-mounted drill inspired by the Wood Wasp ovipositor
- A Hexapod Mars surface walker

Both will be first cut system level designs, where MEMS and associated technology will play a part.

2.11.6. Glossary of Space-Related MST terms

ASIC - Application Specific Integrated Circuit.

ASIM - Application Specific Integrated Microsystem.

FPGA - Field Programmable Gate Array

MCM - Multi Chip Module

Microsystem (MST) - Intelligent miniaturised system comprising sensing, processing and/or actuating functions.

Microelectromechanical Systems (MEMS) - Integrated micro devices or systems combining electrical and mechanical components, fabricated using integrated circuit (IC) compatible batch-processing techniques.

Micromachines - Functional elements only a few millimetres in size which are capable of performing complex microscopic tasks.

Microsatellite - A satellite of mass 10 – 100 kg.

Microtechnology/Microengineering - The technology of small structures/systems where dimensions are typically 0.1 – 1000 mm.

Minisatellite - A satellite of mass 100 – 500 kg.

MOEMS - Micro-opto-electromechanical system.

Nanosatellite - A satellite of mass 1 – 10 kg.

Nanotechnology/Nanoengineering - Defined as structures with dimensions or tolerances less than 100 Nm.

Picosatellite - A satellite of mass << 10 kg, typically with a very high level of integration in silicon.

Small satellite - A generic term for a satellite of mass <500kg.

2.12. MEMS ACTUATORS

Si is the commonest material used in micromachining by virtue of its well established, its good mechanical properties and its suitability for integration with electronics.

	Yield strength (10^9 N/m^2)	Knoop hardness (kg/nm^2)	Young's modulus (10^{11} N/m^2)	Density (g/cm^3)	Thermal conductivity (W/(cm^{o}C)	Thermal expansion (10^{-6}/^{o}C)
Diamond	53	7000	10.35	3.5	20	1
SiC	21	2480	7	3.2	3.5	3.3
SiN	14	3486	3.85	3.1	0.19	0.8
Fe	12.6	400	1.96	7.8	0.803	12
Si	7	850	1.9	2.3	1.57	2.33
Tn	4	485	4.1	19.3	1.78	4.5
Steel	2.1	660	2	7.9	0.329	17.3
Mb	2.1	275	3.43	10.3	1.38	5
Al	0.17	130	0.7	2.7	2.36	25

High aspect ratio devices can be micromachined using X-ray lithography and deep reactive ion etching. Si is an ideal material for micromachining by virtue of its ease of batch manufacturing structures, its good mechanical properties (as light as Al but stronger than steel) and availability of integrated circuit manufacturing facilities. Polysilicon is deposited using chemical vapour deposition typically low pressure chemical vapour deposition using silane: $SiH_4 \rightarrow Si + 2H_2$. Anisotropic silicon etchants such as ethylene diamine pyrocatechol (EDP) attack <100> direction much faster than <111> direction. Highly p-doped silicon with boron acts as an etch stop. Anodic bonding of silicon to glass at 400-500^{o}C with an applied voltage of 400-1000 V across the interface creates a seal that is stronger than either material. Si sensors do not suffer from hysteresis and offer high repeatability [Lang 1999]. The most successful MEMS sensor is the micromachined Si pressure and accelerometer sensor based on the piezoelectric or capacitative effect. Piezoresistance is the change in resistance due to mechanical stress defined by the guage factor: $G = \frac{\Delta R}{R\varepsilon}$ where ε=strain. Capacitance sensors have the advantage of requiring power for only readout circuitry over piezoelectric devices. Such sensors commonly come in 8-pin DIL packages with ADC circuitry and microcontrollers – Motorola 68HC711E9 offers 8-bit microprocessor, 8-bit ADC, timing circuitry, synchronous serial peripheral interface (SPI), asynchronous serial communications interface (SCI UART), 512 bytes RAM, 512 bytes EEPROM, 12 kbytes EPROM. The chief problem with microstructures is stiction due to contact with adjacent surfaces which may be alleviated by using self-assembled monolayers to form hydrophobic surfaces. SiC is a wide bandgap material with high mechanical strength, high thermal conductivity, and chemical inertness which is suited to high temperature applications [Sarro 2000]. The vibratory rate gyroscope has a suspended rotor in resonance through automatic gain control of a trans-resistance amplifier [Howe et al 1996].

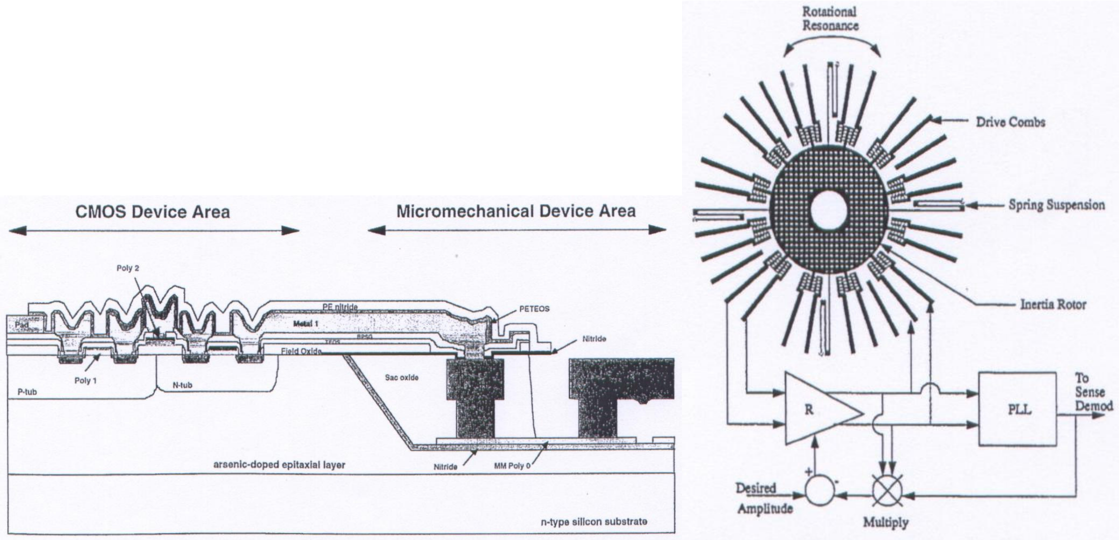


Fig 2-48 (a) Cross section of embedded MEMS integrated technology; (b) Dual input axis vibratory rate gyroscope [from Howe et al 1996]

Rotation of the rotor generates a coriolis torque on the vibrating rotor causing it to oscillate and so detect angular rate. Micromachined integrated gas chromatograph has also been developed. Applications now include scanning near-field optical microscopy and atomic force microscopy. Electrostatic stator wobble micromotors and electrostatic drive are micromachined actuators. Other applications include DNA manipulation, molecular self-assembly and laser microchemistry [Fluitman 1996]. Space application of micromachined systems requires consideration of packaging. In the near term, microsystems offer space missions with integrated antennas on solar cells, microfluidic thermal control, micro-optics [Helvijian & Janson 2000]. Micromechanical louvers covered with aluminised film which may be actuated over a high emissivity coating can provide efficient heat rejection. Micro-heat pipes with diameters ~10 μm may provide high thermal conduction paths for micro-devices. The obvious application for micromachining are satellites-on-a-chip of 10-30 cm dimensions composed of bonded thick wafers where silicon acts as a multifunctional material for structure, electronics, sensors, actuators, radiation shield, thermal control and optics. Such a spacecraft is a stacked multiwafer package. Alternatively, thinned micromachined electronics, sensors and actuators, thin film solar cells and patterned metal antennas on 10-100 μm thick kapton sheets could provide the basis for solar sail missions. Microsensors are well established but microactuators provide the possibility of performing physical actions in its environment. The simplest silicon device is the V-groove formed by anistropic etching which is used in fibre-optic instruments. Integrating circuit microtransducers, typically based on CMOS technology and bulk/surface micromachining, have been developed for a wide range of functions, eg. thermopile imagers, temperature sensors, pressure sensors, ultrasonic sensors, fluxgate magnetometers, etc [Baltes 1996]. Anisotropic etching of the (100) substrate with etching masks and sacrificial-metal layers allows the fabrication of open or closed SiO_2 microstructures such as beams and membranes. CMOS based chemical microsensors with a chemically-sensitive polymer film have been developed for detecting volatile organics in the air [Baltes & Brand 2001]. Changes in mass, temperature and dielectric constant of the polymer due to analyte absorption may be sensed using resonant, calorimetric, capacitative sensing structures respectively. As all rely on the same CMOS fabrication process, arrays of multiple sensors using different polymer films and operating characteristics can be constructed and flip-chip packaged. Smart sensors include signal conditioning circuits for ADC, noise suppression, calibrate against offsets and biases, linear correction, cross-sensitivity correction, hysteresis and drift corrections, etc [Smith & Bowen 1995].

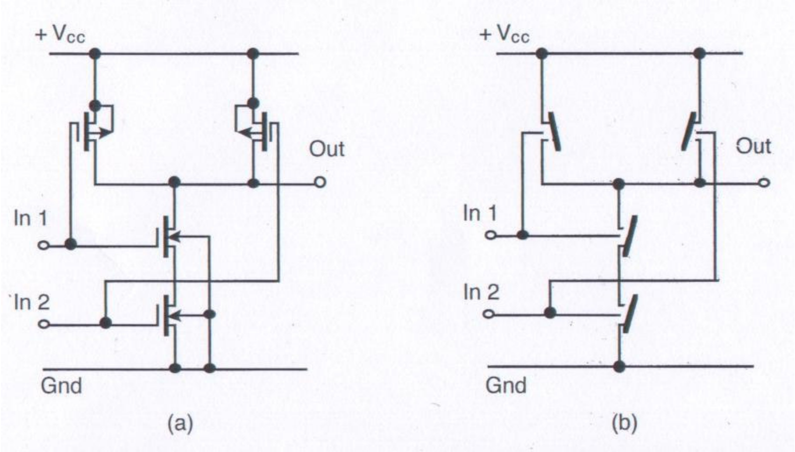


Fig 2-49 FET-based electronic and microswitch-based MEMtronic dual input NAND gates

Microactuators may be based on a number of means: electric, magnetic and flow fields can be generated within spaces; intrinsic actuation is enabled by piezoelectric, magnetostrictive or photorestrictive materials; shape memory is based on volume change; fluid flow can provide driving forces for pumps and valves based on thermal expansion, liquid-to-gas phase change and piezoactuation. One of the major limits to micro-miniaturisation is the use of connectors and harnesses. Another problem is the problem of friction which dominates over inertial forces at microscales, prohibiting the use of gears and joints [Fujita 1998]. One means is to suspend moving parts using elastic supports but this limits displacement. The comb-drive actuator is one example. Its moving part is supported by double-fold beams and is actuated by interdigitated comb-like structures. However, friction may be exploited such as the ultrasonic micromotor that uses a standing wave to drive a rotor or slider; ciliary motion by coordinated vibrations of arrays of cantilevers acting as conveyors [Ataka et al 1993]; impact drive actuators in which small recoiling masses moved by a piezoactuator forces a larger body to move. Friction can be eliminated by using levitation between a superconductor and permanent magnet, or by the use of controlled airflow from micro-nozzles. Other approaches include replacing sliding contacts with rolling contacts, eg. the wobble motor with a smooth ring rotor which rotates eccentrically without slipping at the contact with the shaft.

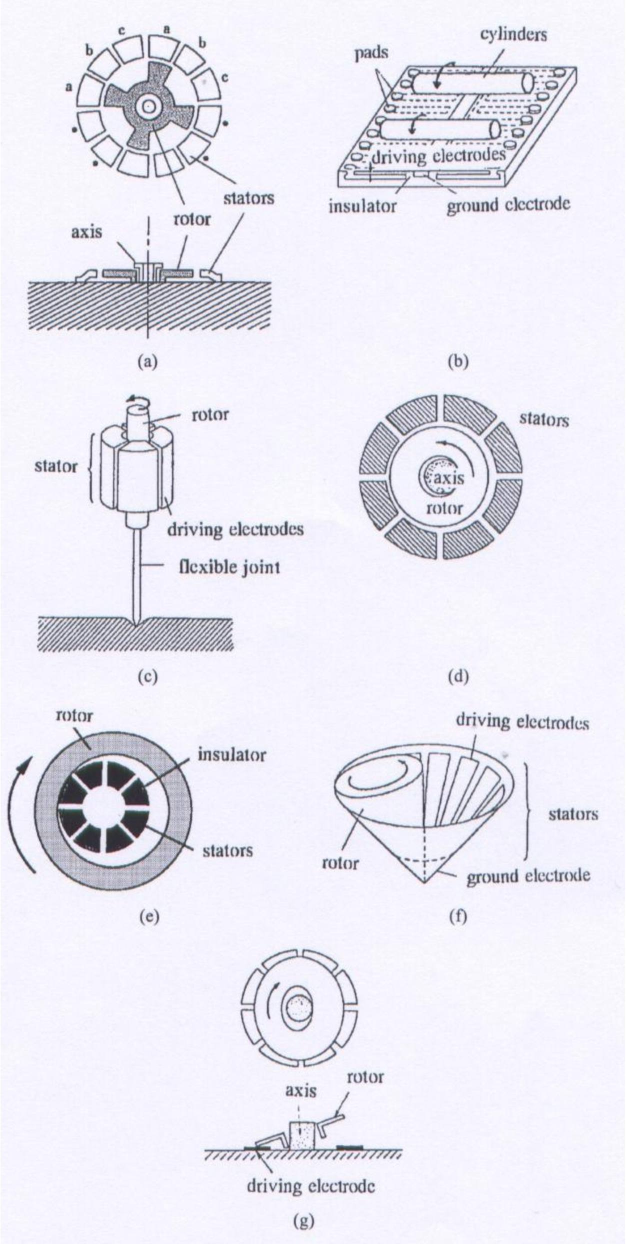


Fig 2-50 Electrostatic micromotor concepts [from Fujita 1998]

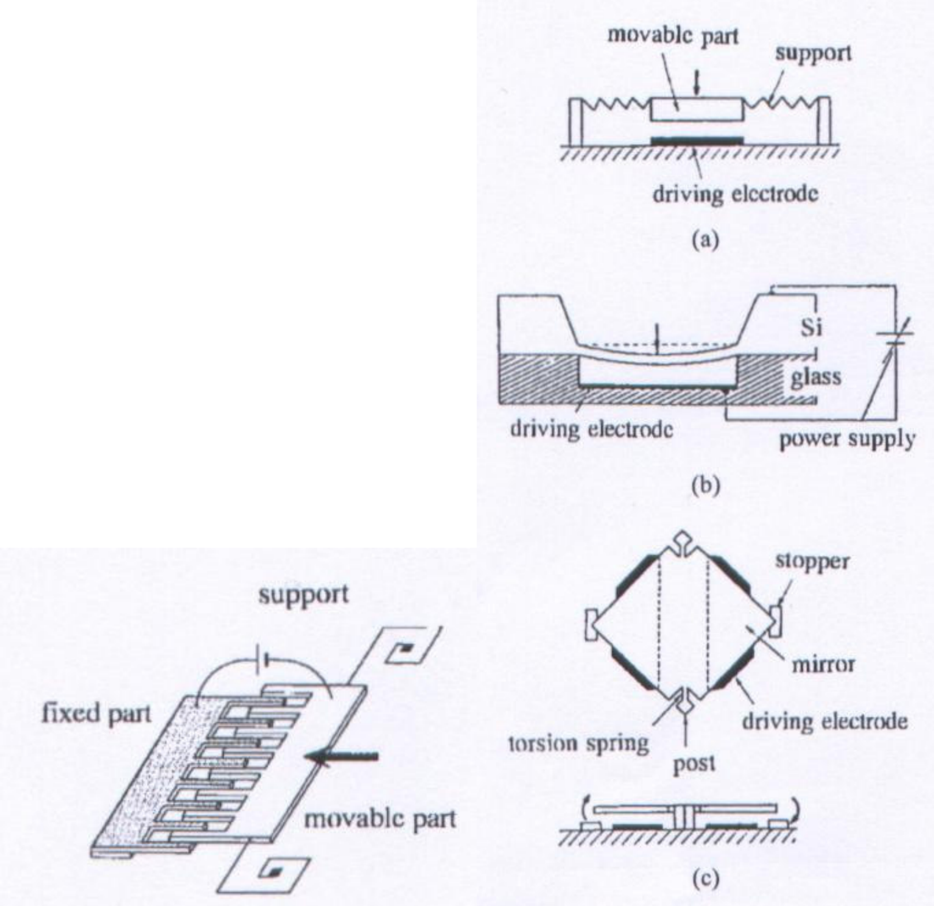


Fig 2-51 Microactuator with flexible support: (a) parallel plate type; (b) membrane deformation type; (c) torsion mirror [from Fujita 1998]

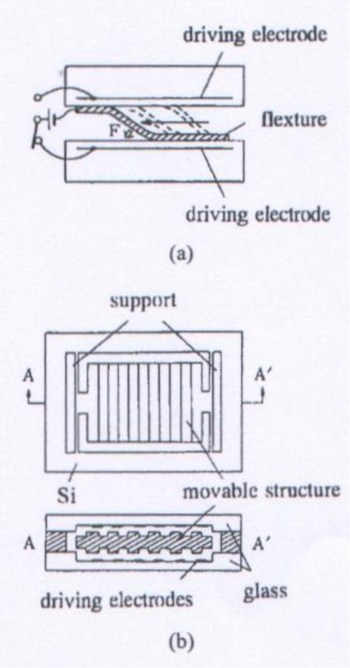


Fig 2-52 Microactuator with elastic motion (a) S-shaped flexure type; (b) surface drive type [from Fujita 1998]

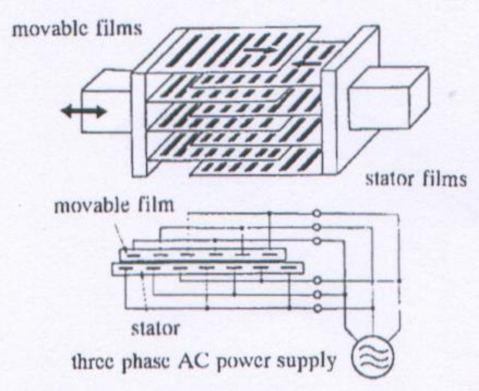


Fig 2-53 Layer film type electrostatic microactuator [from Fujita 1998]

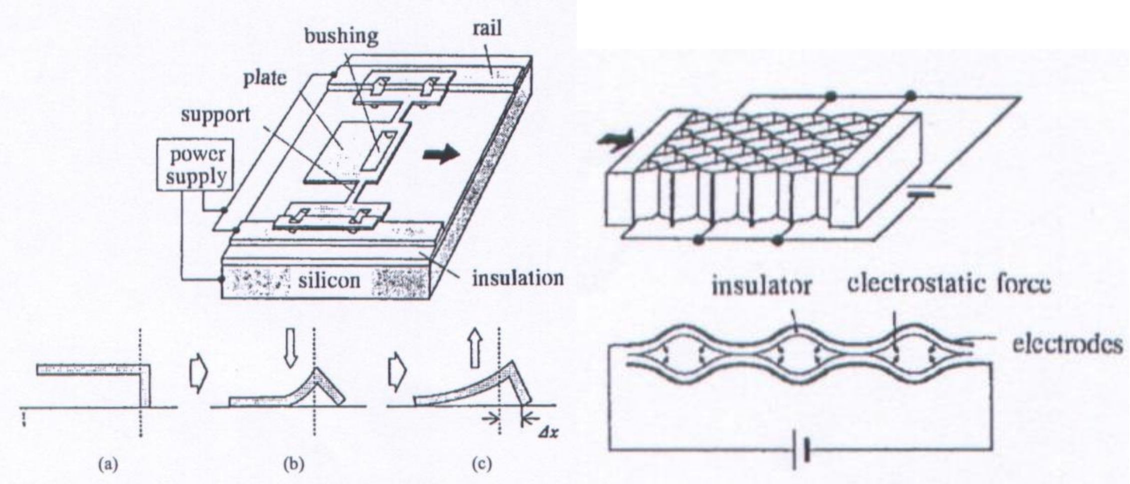


Fig 2-54 (a) Scratch drive actuator; (b) Microactuator with distributed force elements [from Fujita 1998]

Micromotors with diameters if 1/10 mm with speeds of 10^4 rpm have been constructed. A three phase variable reluctance stepping linear motor with three groups of poles with teeth has been demonstrated [Fohse et al 2001]. The stator comprised of a flux guide, three groups of poles with teeth, and meander type coils for exciting each group of poles; the traveller was built from a flux guide and teeth. Similarly, a piezoelectric inchworm rotary motor with a diameter of 4 mm has been demonstrated with a high torque output and linear control of its rotational velocity with frequency [Bexell & Johansson 1999]. A thin polysilicon vibrating ring gyroscope with polysilicon electrodes to sense the ring vibrations has also been fabricated [Ayazi & Najafi 2000]. A common application of microactuators is deflection of light beams by small electrostatically-steerable mirrors and variations on this theme including optical fibre switches, Fabry-Perot interferometers, cavity laser diodes, etc. The micromachined scanning probe microscope composed of a piezoelectrically driven cantilever can provide atom manipulation. Microtechnology is uniquely suited to biotechnology as the typical dimensions of bacteria are ~1-10 μm. Arrays of cantilever actuators which synchronously vibrate can provide the basis for larger forces and displacements than single simple micro-actuators, mimicking the behaviour of biological cilia, eg. bimorph thermal actuators using two layers of polyimides with different thermal expansion coefficients activated by the sandwiched microheater has been demonstrated [Ataka et al 1993].

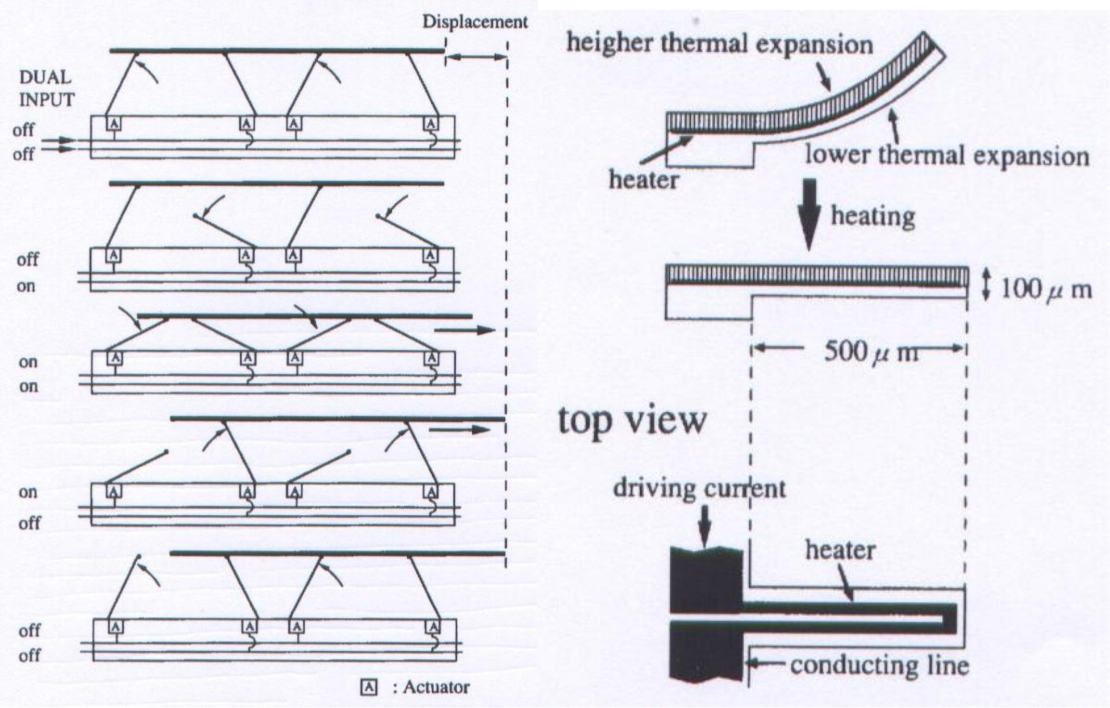


Fig 2-55 (a) Driving principle of ciliary motion system; (b) thermally driven polyimide cantilever actuator [from Ataka et al 1993]

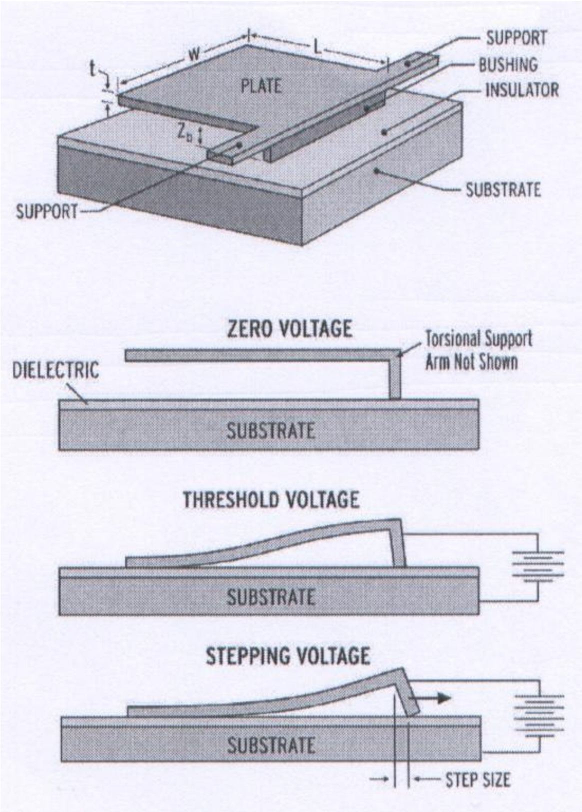


Fig 2-56 Micro-fan system for micro-air vehicle [from Linderman et al 2002]

2.13. NANOSATELLITE TECHNOLOGY

The UK's SSTL (Surrey Satellite Technology Ltd) are pioneers in small spacecraft technology with their highly successful UoSAT series. They have moved away from traditional spacecraft design configurations whereby a framework skeleton is used to mount modules with the various spacecraft subsystems interconnected by a wiring harness. They have adopted a skeleton-less modular design where identical module boxes (but each housing a different subsystem) are stacked vertically to form a body onto which solar panels and instruments can be mounted. The first 6.1 kg nano-satellite SNAP-1 (of which 3.5 kg was payload) was launched in 2000 and was three-axis stabilised. Its primary mission was as a technology demonstrator of a machine vision system capable of inspecting other spacecraft. It carried advanced micro-miniature GPS navigation, camera technology, onboard computing, propulsion and attitude control technologies – all developed in the UK by SSTL. SNAP-1's primary payload was a machine vision system (MVS) which enabled the inspection of other spacecraft in orbit. SNAP-1 used a simple electrical interface for each module comprising a regulated 5V and 7.2 V raw battery power distribution (peak power of 9.1 W of which 2W was for payload) and a single bi-directional CAN (controller area network) bus for data distribution. All modules except the onboard computer (OBC) and MVS contained a standard 8-bit CAN-microcontroller Siemens C515 for telemetry, telecommanding, data transfer (at 1 Mbps downlink) and some onboard autonomy. The OBC and MVS were based around 32-bit StrongARM SA1100 RISC processors, plus external CAN interfaces operated through the StrongARM's built-in SPI interface. Every mechanical module on SNAP-1 is identical sized to house a standrard "Eurocard" PCB (1600 mm x 100 mm x 13 mm). SNAP-1 was constructed from three sets of electronic module boxes connected into a triangular truss. The MVS consists of three ultra-miniature wide-angle CMOS video cameras and one narrow-angle CMOS video camera, together with sophisticated image processing electronics. The MVS was also used to provide medium resolution images of the Earth from SNAP-1's 650 km altitude, near-polar orbit. The near infra-red filter in the narrow angle camera provides good discrimination between land, sea and clouds and allows the camera to produce clear images through the otherwise hazy atmosphere at 500m ground resolution. Using its miniature propulsion, navigation and inter-satellite link systems, SNAP-1 rendezvoused in orbit with its sister spacecraft Tsinghua-1 to demonstrate satellite formation flying for the first time, leading the way to the development of the micro/nanosatellite constellations that is set to revolutionise space exploration in the 21st Century. SNAP-1 was designed and built by SSTL with its own funds in under one year and at an overall mission cost, including development, launch and commissioning, of less then $1.5 million. Already a world leader in innovative spacecraft engineering, SSTL's philosophy of 'affordable access to space' has taken a significant step forward, delivering micro-miniature satellites which can be constructed within very short time frames and at extremely low cost - thus opening up many new possibilities for space exploration to a wider community of users. Earlier this month, SSTL celebrated its 15th anniversary of the Company's founding in 1985 -- since when it has built and launched 14 satellites (with 4 more due this year) and secured contracts to a total value of £64M. With over 100 orbit-years of flight heritage, SSTL now offers a range of small satellites from 6kg nanosatellites; 50-130kg microsatellites and 400kg minisatellites carrying communications, Earth observation and science payloads.

2.14. NANOROVERS

ESA has similarly been interested in nano/micro-robots for planetary exploration. The Micro-Robots for Scientific Application (Micro-ROSA) technology research programme imposed the following design constraints:

Total mass: <4 kg including payload
Payload mass: ~2 kg
Stowage volume: 35x26x20cm
Telecommunications capacity: 1 MB/day via tether to lander
Power consumption: <2W (average), 3W (peak) from lander via tether
Maximum obstacle height or crevasse width: 10 cm
Sensor positioning accuracy: 1mm
Maximum speed: 5m/h forward and backward
Slope negotiation: 15° uphill, 20° downhill

The basic architecture relies on supplying power and data through a deployable tether connected to the lander for operations in the vicinity of the lander. The payload of a rover typically comprises around 5-15% of the rover's mass, but nanorovers increase the payload ratio by off-loading communications and power generation to the lander from which it draws power and data through a tether. The Nanokhod rover has a payload of 1.1 kg for scientific instruments (nominally an APXS, Mössbauer spectrometer and close-up stereo-imager) while its own mass is just 1.45 kg connected to a lander with a 20-30m tether supplying power and data transfer. The tether and the mounting of navigation cameras allows a very high payload-vehicle mass ratio. Such nano-robots are designed to deploy scientific instruments acting as an extended robotic arm with a limited mobility to cover a small area around the lander.

Most of the nano-rover's traverse is assumed to be over nearly flat terrain within 10m of the lander with a potential total traverse of 50-100m within 20-30m of the lander but with some limited obstacle climbing required – this assumption is an optimistic one as Sojourner had great difficulty in negotiating the "rock garden" in its short traverses and the Martian environment is very rocky unlike the Moon. Furthermore, a 100m traversae would require a considerable length of tether. There are three basic designs which have been proposed to meet these nano-rover design criteria. The 5 kg Mobile Instrument Deployment Device (MIDD) under development by DLR is a nanorover comprising a rigid 40x25x20cm chassis with 4 2.2 cm width rigid wheels with a payload capacity of 1.5 kg [Richter et al 1998, 2000]. It is designed for a 50-day lifetime and possesses a 5-10cm obstacle-climbing capability with a traverse speed of 1 mm/s and a range of 10m powered from a tether. Its wheels have a diameter of 19.2 cm and a width of 4.5cm providing a wheel-base of 27.3 cm and a ground clearance of 5.2 cm. The front wheel assembly includes annular metal springs that act as rotating dust-seals. Actuated levers support the front two wheels which can be rotated into an upwards position for stowage and downwards on deployment. This allows alteration of the ground clearance and "kneeling" to point scientific instruments. The 4 wheels are individually driven by dc micromotor/gear assemblies with motor torques ~mNm. Steering is accomplished by differential driving of opposite wheels. It is conceived to be tethered for power and data supply with pay-out capability. The two most innovative designs are Nanokhod (Model A) and SpaceCat (Model B). Nanokhod is a tracked nanorover under development by the Max Planck Institute for Chemistry and von Hoerner & Sulger GmbH, the tracks being enclosed for dust sealing [Bertrand et al 1998, 2000]. It was baselined for the BepiColumbo mission to Mercury. SpaceCat is an innovative tri-wheeled "wheel-walking" prototype nanorover under development by EPFL/Mecanex [Laveria et al 2000, Siegwort et al 1998]. These nanorover designs are limited in their capabilitiesand range, and are more suited to multiple delivery missions. Their power drainage from the lander through the tether is very low defeating the purpose of using lander power – the advantage of generating power from the lander derives in its static nature allowing it a greater area for power generation and heavy battery storage capacity. Such low powers could easily be accommodated from the nano-rover platform. Furthermore, small rovers have a limited obstacle negotiation capability which is a serious limitation on a planetary surface like Mars which is littered with rock fields. These nanorovers essentially operate as extensions to a robotic arm for the placement of scientific instruments within the vicinity of the lander to overcome problems such as those encountered by the Viking landers – the Viking landers' pre-programmed robotic sampling routines were compromised by large rocks at the pre-programmed sampling sites. Even smaller robots have been proposed for the exploration of planetary surfaces – MICROS, a 6 kg ball-shaped miniaturised freeflying spacecraft platform of diameter 230 mm; MANTA (Mars Nano/micro-Technology Aircraft), a micro-aerial autogyro vehicle with VTOL capabilities; Nano-Rover, a very small four spoked-wheeled dual-body rover of <100g to be deployed in swarms ejected rom a lander [Hill et al ?]. The MANTA mass budget was described thus:

Total mass (kg)	2.5
Rotor diameter (deployed), mm	1500
Stowed dimensions (LxWxH), mm	800x500x380
Airlock clearance diameter (mm)	600
Max mission duration (h)	3
Maximum speed (km/h)	100
Normal cruising speed (km/h)	60
Range at max speed (km)	100
Glide path (power off)	1:6

There are a number of considerations that must be accounted for in designing systems of small dimension and mass which may be analysed through dimensionless constants [Vogel 1998]. The first concerns the limits to stress. The ratio of stress on the base of the structure to the compressive strength of the structure's material cannot exceed unity:

$\frac{\rho g h}{\sigma_c} < 1$ where ρ=material density
h=height
σ_c = material ultimate compressive strength

Bone and wood have theoretical maximum height of 8 km compared with granite with 4 km. Similarly, plants and animal morphology is determined by the fact that metabolism and longevity scale with surface area per unit mass which has implications for body sizing and geometry (particularly transportation networks) [Reich 2001]. Size-related scaling may be described by a power law of the form $Y = aW^b$. There is a ¾ power law scaling of metabolic rate against animal mass because these are the maximum values for effective surface area and linear dimensions for a volume-filling fractal network. For plants, there is a 1-power law scale due to planar changes in either length and/or width rather than volume. These scaling laws imply that large animals have long lifespans, slow growth rates and low metabolic rates.

Below a certain size of ~1 cm in length and above a certain size of ~1mm in length, some animals can walk on water using the liquid's surface tension for support. The upper bound is determined by the Bond number which is the ratio of gravitational to surface tension forces:

$Bo = \frac{mg}{\gamma l} < 1$ where γ = surface tension
l = wetted perimeter (length of air-leg-water interface)

An insect of 0.1 g requires a 1.3 mm perimeter across all contacting legs. The lower size limit is determined by the surface tension resistance to locomotion quantified by the Weber number, the ratio of inertial to surface tension forces:

$We = \frac{\rho l v^2}{\gamma} > 1$

The capillary effect is also determined by the balance between gravitation and surface tension. The caplillary rise in columns of liquid are limited by the height of the column which is determined by the Bond number:

$Bo = \frac{\rho g h r}{2\gamma} < 1$ where r = conduit radius
h = capillary height

Similarly, fluid flow through elastic pipes is determined by the opposing influences of Bernoulli's principle and the Hagen-Poiseuille equation. Bernoulli's principle suggests that lower pressure results from faster flow through the pipe. Hagen-Poiseuille's equation suggests that faster flow requires higher pressure as pipe walls exert resistance. Their ratio is given by:

$\frac{B}{HP} = \frac{\rho v r^2}{16\mu l}$ where $d = \frac{\rho v^2}{2}$ =dynamic pressure
μ = dynamic viscosity
ρ = fluid density

This is a version of Reynold's number which quantifies the ratio of inertial to viscous forces. In most physiological circulatory systems which are characterised by thin pipes, the Hagen-Poiseuille equation is dominant.

3. Spacecraft Systems Engineering

In TN1, consideration was given to the nature of modularity, hierarchy and pleiotropy in biological systems. A biological organism is a complex system that emerges through the interaction of large numbers of genes. Pleiotropy is based on the fact that some mutations can have a major effect on morphology. Pleiotropy denies the simplistic one gene – one character model. According to Wright's universal pleiotropic hypothesis, pleiotropy is universal and can generate a stabilising selection effect on otherwise neutral characteristics due to genetic correlations and pleiotropic effects on fitness [Baatz & Wagner 1996]. Pleiotropy serves the function of reducing the asymptotic rate of evolution by stabilising selection. Without pleiotropic effects, the asymptotic rate of evolution may be given by:

$\dot{E}_0 = 2\sigma N_e V_m$ where σ = mutational variance

N_e = effective population size

V_m = selection intensity

Pleitropy reduces this asymptotic rate of evolution. However, the genome is organised into relatively discrete "genetic nets" or gene modules, each coding for functionally independent characters. Only limited pleiotropy exists between such modules.

Ecological robotics is based on five fundamental principles [Duchon et al 1997]:

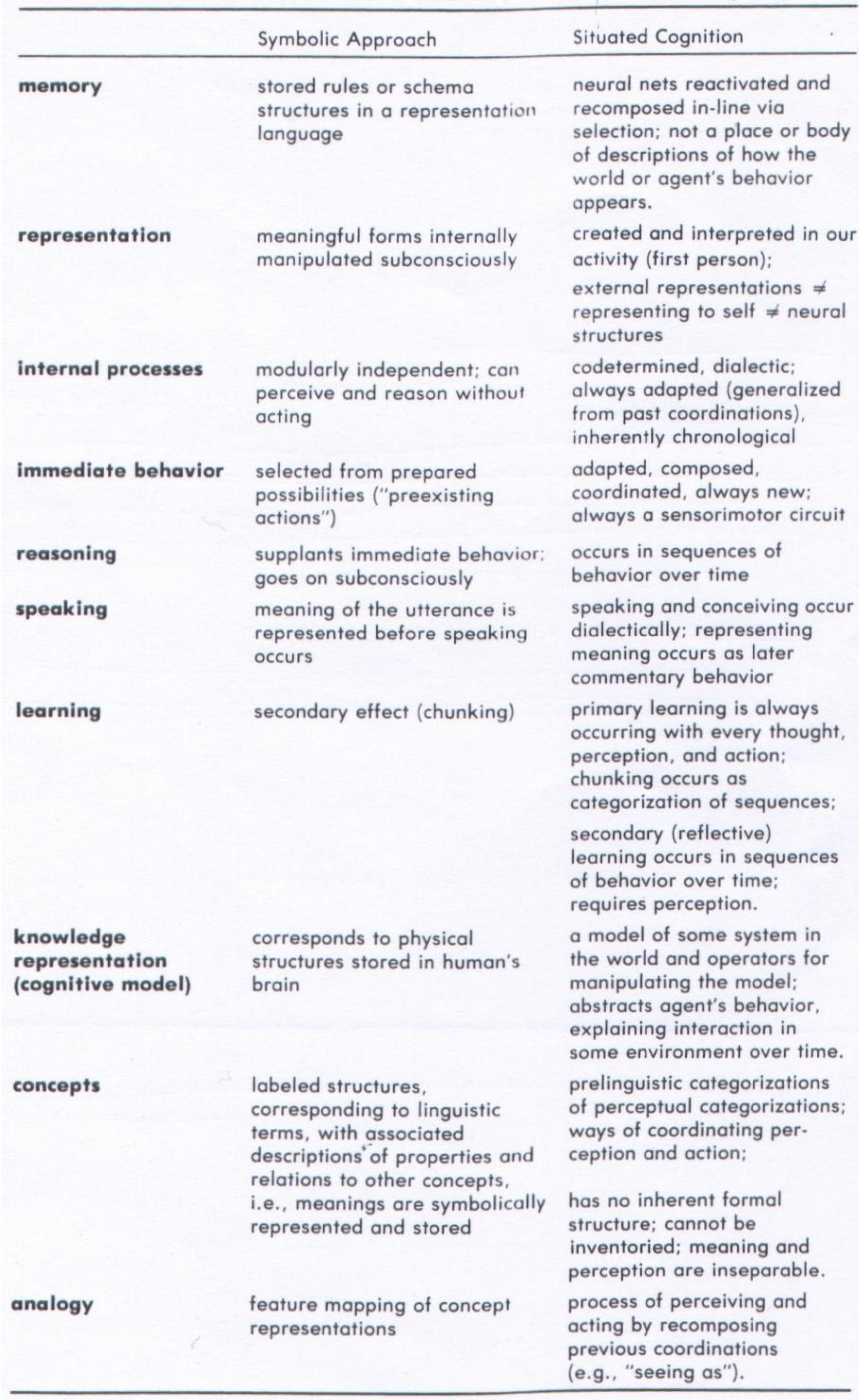
(i) Agent and environment are part of the same system
(ii) Agent's behaviour emerges from the dynamics of this system
(iii) Agent's task is to map information into its control parameters to achieve the desired tasks
(iv) Environment provides sufficient information to achieve this
(v) No central model of the environment is required.

Situated cognition rejects the notion of symbol processing [Clancey 1993]. In all cases, these models do not consider the cognitive processes that are coordinated, adapt and are relative to the way in which they are used. Similarly, DNA sequences are not symbols as they are not interpreted by the agent possessing them but they do constitute a symbolic code which are interpreted by the agent's biochemistry. There are five major claims to situated action [Clancey 1993]:

(i) representation storehouse model of memory is incorrect
(ii) schema models incorrectly treat categories as prescriptive and fixed
(iii) perception-cognition-action are not separate processes but occur together as coherent coordinations of activity
(iv) rules or laws do not underlie human cognitive activity
(v) situated cognition is concerned with:
    (a) agent located within its environment
    (b) plans and representations are recreated and recoordinated into activity according to the situation rather than stored
    (c) embodied perception and action are simultaneously coordinated processes

(d) learning is central to human cognition

(e) behavioural regularities emerge



	Symbolic Approach	Situated Cognition
memory	stored rules or schema structures in a representation language	neural nets reactivated and recomposed in-line via selection; not a place or body of descriptions of how the world or agent's behavior appears.
representation	meaningful forms internally manipulated subconsciously	created and interpreted in our activity (first person); external representations ≠ representing to self ≠ neural structures
internal processes	modularly independent; can perceive and reason without acting	codetermined, dialectic; always adapted (generalized from past coordinations), inherently chronological
immediate behavior	selected from prepared possibilities ("preexisting actions")	adapted, composed, coordinated, always new; always a sensorimotor circuit
reasoning	supplants immediate behavior; goes on subconsciously	occurs in sequences of behavior over time
speaking	meaning of the utterance is represented before speaking occurs	speaking and conceiving occur dialectically; representing meaning occurs as later commentary behavior
learning	secondary effect (chunking)	primary learning is always occurring with every thought, perception, and action; chunking occurs as categorization of sequences; secondary (reflective) learning occurs in sequences of behavior over time; requires perception.
knowledge representation (cognitive model)	corresponds to physical structures stored in human's brain	a model of some system in the world and operators for manipulating the model; abstracts agent's behavior, explaining interaction in some environment over time.
concepts	labeled structures, corresponding to linguistic terms, with associated descriptions of properties and relations to other concepts, i.e., meanings are symbolically represented and stored	prelinguistic categorizations of perceptual categorizations; ways of coordinating perception and action; has no inherent formal structure; cannot be inventoried; meaning and perception are inseparable.
analogy	feature mapping of concept representations	process of perceiving and acting by recomposing previous coordinations (e.g., "seeing as").

Table 3-1 Comparison of symbolic and situated approaches to cognition [from Clancey 1995]

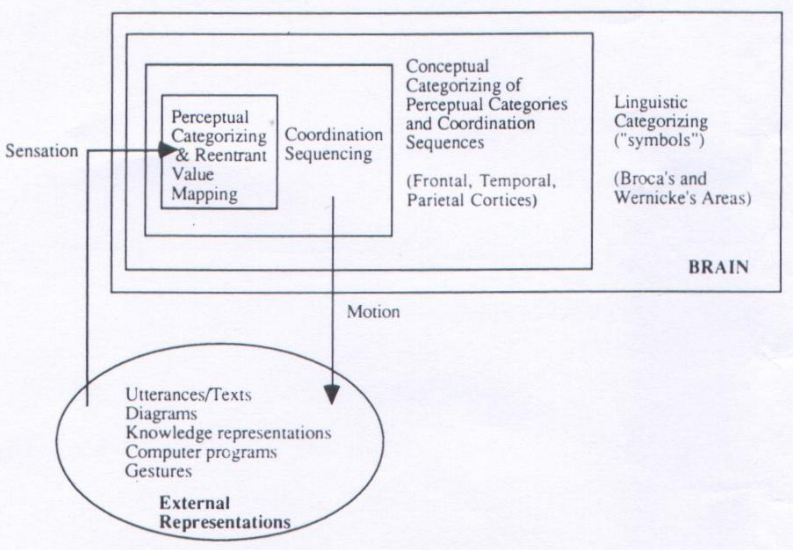


Fig 3-1 Situated action view of sensorimotor coordination [Clancey 1993]

Cognition is a physical skill and knowledge cannot be transferred from one brain to another as rules and facts [Clancey 1995]. Cognition cannot be separated from physical behaviour. The neural processes that coordinate perception and action are created during activity through a process of reactivation, competitive selection and composition rather than retrieved and reconstructed from memory. Learning is a continuous process as part of ongoing perception-action coordination. Perception is fundamentally an action process which may be accomplished through dynamic global mapping. These global maps contain multiple reentrant local sensorimotor maps that interact with other neuronal groups. Dynamic selection in local maps dynamically creates motor behaviours to sensory inputs which produce further sensory inputs continuously. Categorisation occurs by sensorimotor activity selecting neuronal groups that generate the appropriate behaviours according to internal value criteria. The internal value criteria are defined by emotion which form an integral part of cognition. Schema are dynamic hardware configurations of neural systems which are continuously coordinated and adapted to each other. Those activations which are successful are reinforced biasing such copositions in the future. Regularities in behaviour develop because perceptual-motor coordinations are correlated over time. Symbolic (linguistic) processes are subsumed and grounded by sensorimotor coordination – language is based on symbolic categorisation within phonological and syntactic constraints. Human individuals coordinate their activities interactively through behaviour providing the basis for sociality and the formation of linguistic communities and common social conventions. It is this social process that provides the basis for understanding and interpreting the behaviours of others. Learning knowledge is socially mediated. This notion of situated cognition may be regarded as an extension of Karmiloff-Smith's view of human cognitive development as a process of ongoing redescription.

Biological organisms exploit modularity and hierarchy as the means to accommodating the control of large amounts of information. The hierarchy may be represented as a uniform tree structure with a branching ratio b and depth d so that the total number of nodes $N=b^d$. The multihierarchy provides a compromise between rapid local response and global higher level response [Hogg & Huberman 1998]. The multihierarchy comprises a collection of overlapping hierarchies which offers higher stability than single hierarchies. The human mind as a set of independent modules each evolved in response to specific environmental pressures, eg. grammar processing, face recognition, objecthood recognition, animacy, social inference, concept of quantity and number, theory of mind, etc. Poverty of stimulus suggests that such cognitive capacities cannot be learned from scratch. Their major characteristics are:

(i) domain specific
(ii) species universal
(iii) encapsulation
(iv) genetically specified

Inductive learning requires an association between two stimuli through repeated pairings. However, some associations are more readily learned than others indicating a bias towards learning contingencies that have significant survival implications. Primates are predisposed towards fear responses to specific classes of animals such as spiders and snakes (which can be poisonous). Similarly, taste aversions to food that causes illness is also well established. The Garcia effect is the most dramatic example of evolutionary biases to learning. Rats are allowed to drink water with bitter quinine while in a room of flashing lights. Rats which are subsequently subjected to electric shock will avoid drinking while the lights flash. Rats which are subsequently induced to produce nausea will avoid the bitter water. Hence, certain cues and responses are naturally associated with each other and readily learned. Human infants are predisposed to interpret the world in terms of objects and agents whose behaviours are constrained by different principles. There are other cognitive biases such as causality, categorisation and social reasoning. Biological preparedness in humans includes:

(i) distinguish social agents from other objects
(ii) focus attention on facial expressions
(iii) engage in reciprocal social interactions with other agents

This allows learning contingencies between agents' actions and their consequences.

Modularisation may occur through canalisation such that the module develops despite environmental variations [Cummins & Cummins 1999]. The nervous system is highly plastic during development in affecting types of cells, locations of cells and their synaptic interconnectivity. However, the developing brain is not entirely plastic as undifferentiated precursor cells will express the characteristics of the brain region to where they migrate. This provides the basis for biological preparedness which ensure that specialised cognitive functions. For instance, binocular columns appear in the visual cortex during a critical period of the infant's visual experience. Similarly, line orientation cells have preferred visual orientations at birth which become progressively selective to particular orientations to match visual experiences. In language development, all babies (including deaf ones) babble vocally and healthy babies can hear all phonemes in human language which in their first year diminish to only those of their language community. Newborns have a bias to look at faces and by 10 weeks can distinguish among emotional facial expressions. Within their first year, infants observe parental facial responses to their behaviours (social referencing) and by 2 year of age can understand another's preferences, goals and desires. By age 3, children can identify violations of social rules. The development process, despite subjected to environmental variations, achieves a particular end state.

The lessons for spacecraft systems design are threefold:

(i) modularity is essential in any complex system such as a spacecraft;
(ii) traditional spacecraft modularity by subsystems may not be the best approach, though what the best approach is is not clear;
(iii) practical issues impose inertia in the approach to the design of spacecraft.

A compromise solution to spacecraft design philosophy may be the "mechatronics" approach, replicating Brooks' methodology but which still fits within a traditional engineering philisophy. The spacecraft is treated as a complete system with inputs and outputs. The payload of the spacecraft is not treated separately but as an integrated, indeed primary, output of the space mission – its behaviour. These outputs drive the overall spacecraft design with the constraints being the inputs. Mapping the inputs and the outputs is the spacecraft control system – this includes, but is not exclusively restricted to, the attitude and orbit control systems. The environment also acts as a feedback mechanism to the spacecraft. This provides the basis for the modular division. The inputs to the control system are then considered (matter, energy, and data) – structure (matter), power system (energy), avionics (data). The hierarchical breakdown is then applied. The spacecraft bus becomes a fully supportive platform for the payload. Inputs to achieve the mission goals include:

(i) systems analysis based on mechatronics approach
(ii) payload-driven goals – the primary outputs
(iii) the control system as the core of the spacecraft
(iv) the interaction of the environment with the system
(v) the services to the control system – matter, energy and data
(vi) avionics breaks down to C&DH system and rf communications system
(vii) power system breaks down to power generation, storage, conversion/distribution and dissipation (thermal control)
(viii) structure breaks down to materials selection and structural configuration

This proposed compromise to space systems design maintains synergy with current modularity practice but stresses the central emphasis on the payload and the control system – a mechatronics approach. This merely represents one solution – obviously, technological advances such as multi-functional structures will render tight modularity more difficult but some approach to modularity and hierarchy is essential.

4. Onboard Propulsion Systems

The propulsion subsystem generates forces which act on the centre of mass of the vehicle. Propulsion systems are distinguished by comparisons between their specific power, exhaust velocity and thrust acceleration. For example, electric rockets have high exhaust velocities whereas chemical rockets offer high power. Arrays of digital propulsion microthrusters for attitude control and station-keeping for microsatellites have been constructed from a three layer sandwich containing polysilicon microresistor initiators as the rear layer, thrust chambers within 1.5mm thick glass in the middle layer and rupture diaphragms (0.5 μm thick SiN) in the top layer [Lewis et al 2000].

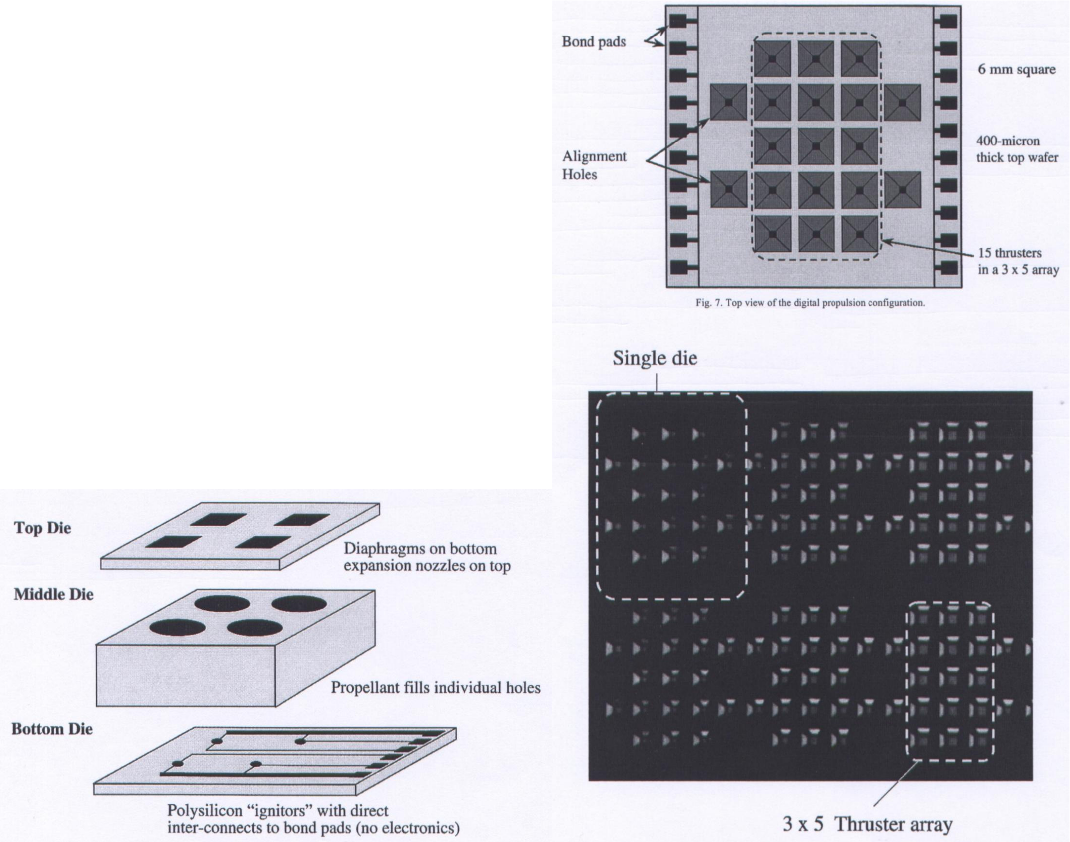


Fig 4-1 (a) Digital propulsion microthruster chip; (b) Diaphragm layer wafer of six dies [from Lewis et al 2000]

Each thrusters pixel is ~10^2 μm x 10^2 μm in size. All three layers are bonded by cyanoacrylate. Propellant (such as lead styphanate) is contained in each individually sealed chamber which ignites when the resistor is activated, rupturing the diaphragm and thus generating impulse from the ejection of the high pressure fluid. A single wafer contains 10^6 thrusters, each capable of generating 10^{-4} Ns of impulse. The array can be commanded to fire individual thrusters, groups of thrusters, in sequences and produce vectored thrust. This approach eliminates the requirement for tankage, fuel lines, valves and moving parts and provides for integration within the spacecraft structure.

We do not consider rocket propulsion as this capability is rare in the biological world. We restrict ourselves to environments that bear resemblance to the Earth's biospheric habitat, ie. planetary surfaces and atmospheres.

4.1. LOCOMOTION SYSTEMS

4.1.1. Land Locomotion

Most molluscs are sessile and have only rudimentary nervous systems while cephalopods are mobile and possess highly complex nervous systems. Unlike in mammals, however, their optic nerves connect to the back of the retina so there is no blindspot. Their brains are annular around the oesophagus. Their blood is green due to copper-based haemocyanin. There is a grounding of sensorimotor control through the interactions of the agent with the environment which deny the symbolic "brain-a-vat" model [Brooks & Stein 1994]. All forms of locomotion require an organism to generate sufficient forces to overcome gravity to propel the body, and to stabilise body orientation through coordination of its limbs, and orient the body in the direction of the goal. Most animals are capable of finding distant, out-of-sight mates, shelter and food usually by tracking odours through their chemical gradients. Most biological forms of locomotion are based on rhythmic motion, eg. gaits in legged animals. Legged locomotion offers considerable advantages over traditional wheeled or tracked locomotion over complex and unpredictable terrain. Most rapid insect locomotion ~2.5 body lengths/s results from the interaction of feedforward motor pattern and visco-elastic properties of the mechanical system – preflexes – to enable accommodation to unstructured environments [Cham et al 2000]. Furthermore, the cockroach can scramble over obstacles up to three times its body height. Running animals act as virtual spring-mass systems similar to inverted spring-loaded pendulum whilst rejecting perturbations and receiving little in the way of sensory input. The basic motor pattern remains essentially invariant over rough terrain enabled through a feedforward pattern on its mechanical structure, ie. preflexes of nonlinear, passive visco-elastic properties of the mechanical system itself which respond instantaneously – compliance as an efficient means to exchange energy. Similarly, passive damping in joints lie at criticality. In the cockroach, the rear legs angled backwards act as thrusters with the centre of mass lying to the rear of the body. Front legs are angled forward to provide braking. Transitions within gaits are initiated not by sensory feedback from the feet but from the feedforward pattern as a function of frequency and duty cycle of leg movement. Integration of the second order differential equation yields:

$$x_i(t) = e^{A_i t} x_i(0) + (1 - e^{A_i t}) x_{eqm}$$ where x_{eqm}=equilibrium point of mass-spring-damper system

Perturbations will dissipate if the eigenvalues have a magnitude of under unity. The stiffness and lengths of the legs and their angles are may altered to change the equilibrium position while damping alters the rate of motion towards equilibrium. Robot II had six legs, each with 3 degrees of freedom driven by dc motors, and used distributed control with modules for posture, gait, leg coordination, leg reflexes and joint control based on insect and crustacean locomotion [Quinn et al 2000]. Robot II could traverse a series of slats using its searching reflex and climb over obstacles as high as its body height using its elevator reflex. Robot III was based on cockroach locomotion though without replicating the 8 degrees of freedom typical of insects. The 3 DOF hind legs push the animal forward while the 5 DOF front legs operate more like arms by probing the terrain and acting as brakes. The 4 DOF middle legs allow rotation of the legs during climbing. The centre of mass of Robot II lies at the body-coxa joints of the rear legs as in the cockroach. There are three control modules: posture control, swing control and stance control. Posture control monitors the centre of mass position and is active continuously. Insect walking is enabled through a distributed set of six coupled relation oscillators, one per leg, which generate rhythmic frequency-coded spikes to combinations of motoneurons in each leg. During climbing, the centre of mass must be elevated which in the cockroach is achieved by rotating the tibia of the middle legs more perpendicular to the ground, and pushing on the hind legs. Swing control and stance control are defined by the gait. During walking, the foot is placed on the ground at the anterior extreme position. The redundancy of the inverse kinematics of the middle and front legs was optimally solved according to minimum energy consumption constraints at a number of points and a neural net trained on this data set to provide continuous solutions. Stance control monitors ground reaction forces and extends the leg until it reaches its posterior extreme position. For complex terrain, it is necessary to monitor load sensors to determine the amount of force required to continue extension until the required joint angles are attained. To ensure stability, in animals, when muscles shorten their tension generation decreases and proprioceptors provide negative feedback to disengage stance control when the leg reaches its required joint angles. During the stance phase, the joint feedback gains are increased to increase its load-bearing capacity. RHex is a 7 kg biomimetic hexapod with a sprawled posture similar to the cockroach *Blaberus discoidalis* to enable running [Klavins et al 2000]. It uses one degree of freedom per leg at the hip with a 20 W brushless dc servomotor, each leg being fully compliant (preflexes). This is a version of the spring inverted pendulum oscillator. It uses a two phase periodic signal – slow speed corresponds to contact with the ground to propel RHex forward and a fast speed for the greater arc over the top of the leg joint.

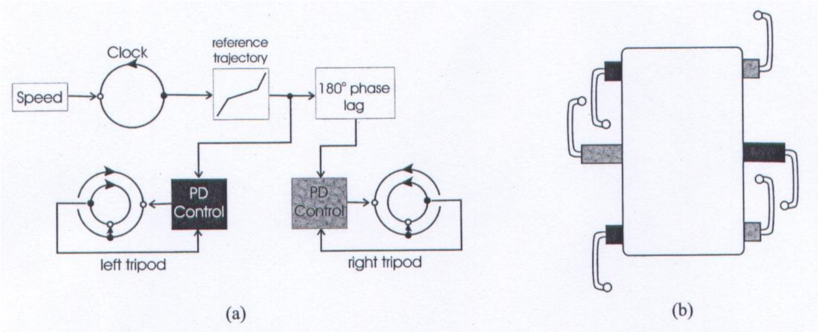


Fig 4-2 Two stroke phase-antiphase clock signal for PD controllers at each hip; (b) RHex leg configuration [from Klavins et al 2002]

Central pattern generator is an open loop feedforward method which may be modelled as:

$\dot{\phi} = \frac{2\pi}{T_c}$ where ϕ=phase

T_c=oscillation period (which corresponds to energy)

The Scorpion robot was an 8-legged robot where each 3 DOF leg comprised a thoracic joint for horizontal protraction/retraction, vertical basalar joint for elevation/depression, and vertical middle joint for flexure/contraction, and a passive foot joint.

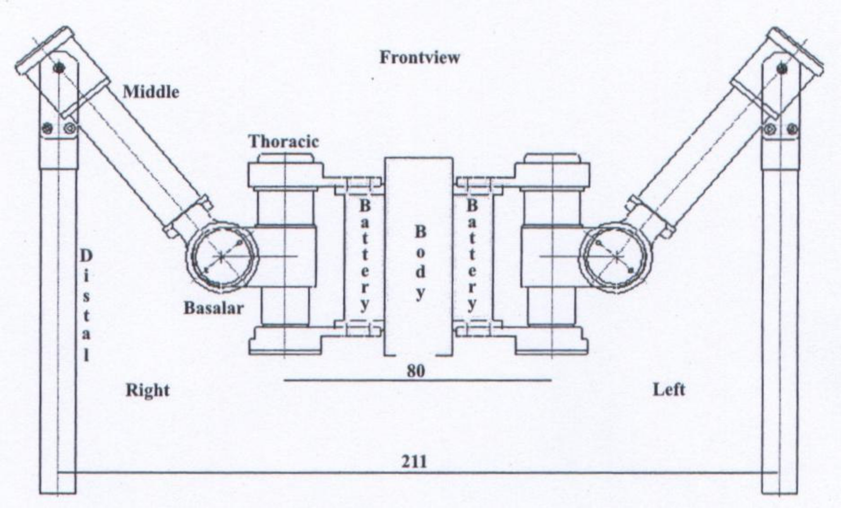


Fig 4-3 Mechanical design of Scorpion legs

The distal segment includes a spring damped compliant element with a potentiometer to measure contact and a potentiometer to measure foot loading and absorb footfall impulses. A high payload capacity was enabled by using high ratio planetary gearing with powerful dc motors. Each leg was capable of taking ¾ of the total robot weight and enabled climbing over obstacles exceeding the robot's height. A central pattern generator generates rhythmic motion for plane surfaces but cannot accommodate obstacles. Fast reflexes invoked by certain sensory conditions such as encountering obstacles were built in to override the CPG. When the thoracic joint values increased rapidly in conjunction with high angular displacement error, a reflex which moves the leg backward and upward and then forward is invoked. Scorpion was equipped with forward vision, ultrasonic and infrared sensors and two front bumpers. A network of one central computer for overall control and many local microcontroller units for local leg driving connected through a serial CAN-bus was adopted. Scorpions use the same gait – L4-R3-L2-R1 and R4-L3-R2-L1 with a phase delay ratio of 0.1 between contralateral legs. Sine functions were used for smooth continuous movement. During stance, horizontal joints push the body forward.

Small insects like crickets overcome the inefficiency of ground locomotion at small scales by jumping. The cricket has powerful femurs on the rear legs which jumps by flexing the extensor to full tension and suddenly releasing it. Hopping robots emulate grasshoppers in order to minimise energy costs for wide area exploration [Martinez-Cantin 2004]. Hoppers can also overcome obstacles several times larger than the robot, particularly in low gravity environments. Hopping may be accomplished with a spring, motor and gearing which stores energy in the spring for the jump.

The spinal cord lies at the centre of motor control in legged vertebrates and has a reconfigurable modular heterarchical organisation for different tasks [Giszter 2000]. Each module is a motion primitive (holon). There is a collection of separate motion primitives at the spinal level which are recruited by central pattern generators for different behaviours. Motor primitive is defined as fixed group of muscles with motoneurons and afferent circuits which act as a unit to generate a fixed set of motor outputs. This muscle activity is constrained by the joint and limb configuration and motor primitives may be represented as a biomechanical force field which maps forces in the limb to the limb's configuration as the basis of behaviour generation. Force field primitives are active force fields defined by a force vector resultant from both feedforward and feedback circuits. The observed force field primitive has the form:

$F(r,\dot{r},t) = a(t)\phi(r,\dot{r})$ where r=kinematic configuration

a(t)=scaling factor

$\phi(r,\dot{r})$=fixed field potential structure

Smooth force fields with constrained degrees of freedom may be constructed from such motion primitives through linear combinations of non-conservative translational and rotational fields:

$F(r) = \sum_i A_i\phi_i(r) + \sum_i B_i\psi_i(r)$ where ϕ=translational potential field

ψ=rotational potential field

These force fields generate limb trajectories (typically straight line) from computation of limb joint position:

$$\theta_i(r,\dot{r},t) = A_i a(t)\phi_i(r,\dot{r})$$

During a walking gait, an animal uses gravitational energy storage to swing like a pendulum to reduce the work of accelerating the inertial load of the legs. All animals walk in a dynamically similar manner at a given Froude number. The Froude number is defined by the ratio of inertial force to gravitational force:

$Fr = \frac{v^2}{gl}$ where v = walking speed

l = hip-to-ground distance

To keep storing energy at higher speeds, animals increase the amplitude (stride length) of walking rather than the frequency of motion. All animals reach a maximum amplitude at a Froude number of ~0-5-0.6. From then, animals shift gait into a trot or other gait that exploits elastic energy energy storage in muscles and tendons rather than relying on gravitational energy. For a typical human adult, the transition occurs at around 5 mph. The transition occurs at the same Froude number despite variations in g. Similarly, trot-to-gallop transition for quadrupeds occurs at a Froude number of ~2-4. The basis of rhythmic motion is the oscillator whose natural dynamics causes cyclic behaviour. This may be through pacemaker neurons. Typically, these oscillations have regular periodicity. Networks of such oscillator circuits – coupled oscillator networks - interact with each other to generate complex behaviour patterns. Animal limbs are controlled by rhythmic electrical signals generated by central pattern generators (CPG). Some animals possess only one gait but others possess a repertoire of gaits depending on the speed of locomotion. Quadruped locomotion is controlled by four coupled oscillators. The seven most common quadrupedal gaits are trot, pace, bound, walk, rotary gallop, transverse gallop, and canter. In the trot, the legs are linked in diagonal pairs – front left and back right hit the ground together, then front right and back right. In the bound, front legs hit the ground together then the back legs (eg. dogs). In the pace, the two left legs hit the ground, followed by the two right legs (eg. camels). For the bound, pace and trot gaits, the four oscillators are grouped at two out-of-phase pairs: front/back, left/right and diagonal. The walk is more complex: front left, back right, front right, back left. The walk is a circulating figure-of-eight pattern. In the rotary gallop, the front legs hit the ground with the right/left slightly later than the left/right leg, then the back legs hit the ground with the left/right slightly later than the right/left (eg. cheetah). The rotary gallop is a mixture of the pace and bound. The transverse gallop is similar but with a reversed sequence for the rear legs. The transverse gallop is a mixture of bound and trot. The canter is more complicated and its control is not well understood: front left leg, then back right, then the other two legs simultaneously. The horse uses the walk, trot, transverse gallop and canter. The pronk – a rare gait seen in young deer – involves moving all four legs simultaneously. It is the most symmetric gait and involves synchromeity between all four oscillators.

CPG neurons of the caudal spinal cord control hindlimb activity while the forelimbs are controlled by CPG neurons in the rostral spinal cord. Coordination is achieved by propriospinal neurons. These same circuits provide the basis for human bipedal walking and arm swinging but human forelimb coordination is based on an evolutionarily recent direct cortical-motoneuronal system [Dietz 2002].

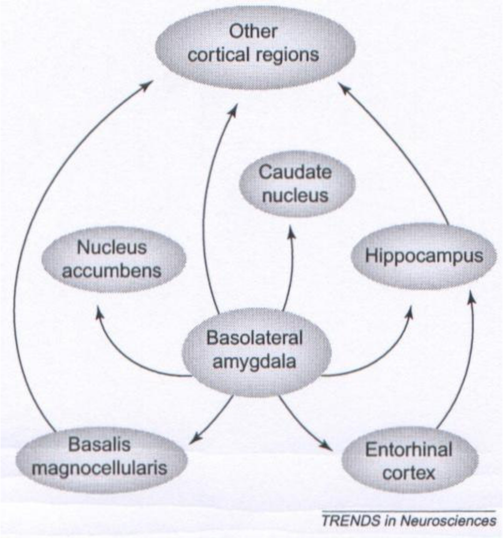


Fig 4-4 Projections from basolateral complex of amygdala to other areas involved in memory consolidation [from Dietz 2002]

Ayers et al (1998) have developed a robotic lobster whose behaviour is based on a general neural model comprising a command neuron, a coordinating neuron and a central pattern generator with sensory feedback from proprioceptive and exteroceptive sensors and phase and amplitude modulating reflexes. Central pattern generation output is modified by peripheral sensory feedback so sensory feedback is not essential for generating motor programs. The central system comprises the CPG to control the muscles of each limb, coordinator to select gaits and command neuron which modulates the CPG behaviour. Peripheral component comprises the sensors, phase modulating reflexes to reset timings of CPG and amplitude modulating reflexes to alter motor output amplitude. Crustacean muscle functions as a contractile element (tension) in series with an elastic element (due to tendons) both in parallel with an elastic component (from muscle cell membranes). These are controlled by motor neurons. Shape memory alloys in antagonistic pairs are suitable muscle emulators controllable proportionally by pulse trains.

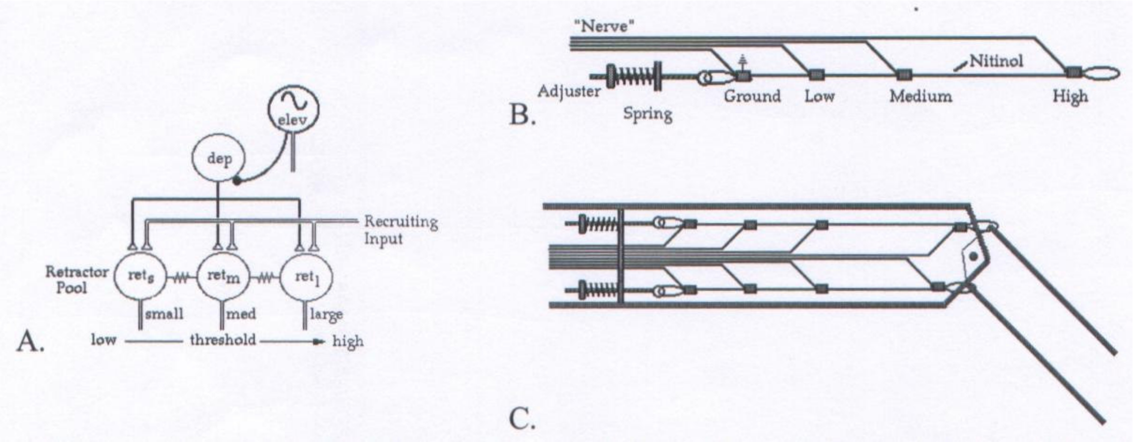


Fig 4-5 (a) Neuromuscular recruitment network (b) Nitinol actuator (c) Antagonistic actuator pairs [from Ayers et al 1998]

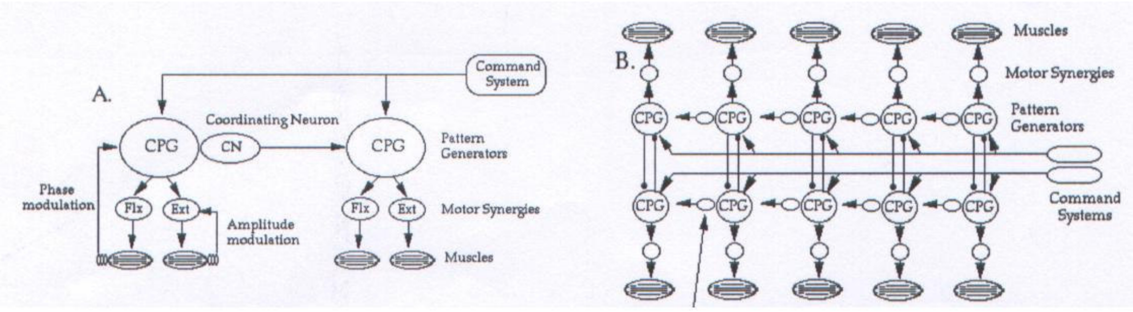


Fig 4-6 Configuration of command, coordinating and CPG neurons for (a) ambulation and (b) undulation [from Ayers et al 1998]

The robo-lobster uses its three jointed limbs for walking on the shore bottom. Limb muscles are controlled through the swing phase and stance phase. This model was implemented on a system of finite state machines (defined by next-state and output functions which may be implemented as look-up tables in RAM) – three control actions were implemented: elevator/depressor, protractor/retractor/ and extensor/flexor controlled by the CPG, coordinatir and command systems. Sensor input was both interrupt-driven and polled – exteroreceptor data is interrupt-driven while inclinometer data is polled. This basic system is enhanced by dedicated processor based acoustic and magnetic sensors for object detection. CPG-based system is suited to segmented undulatory motion coordinated by contraleteral and ipsilateral systems. However, CPG is limited in its gaits in a real uncertain world as its period is tuned to the natural frequency defined by the leg stiffness which in turn imposes a maximum speed. Reflexes based on closed loop feedback must be used. However, preflexes can alleviate this requirement.

The most fundamental capability is orienting to novel stimuli which affords survival value for all types of organism. Visual recognition of objects requires mapping of visual sensations onto stored mental representations based on shape recognition. The central nervous system is required to produce specific motor patterns to coordinate movement. Neural pattern generators reside within the central nervous system that form the basis of rhythmic movement through timing of motoneuron discharge [Stein 1978]. They are activated by command neurons of which there are two types: trigger command neurons which elicit motor sequences that last longer than the stimulus (eg. giant interneurons within invertebrates and lower vertebrates), and gate command neurons which activate tonic motor systems involved in posture and phasic locomotion motor systems. In invertebrates and lower vertebrates, single command neurons exist (eg. anterior burst neuron in crustacean stomatogastric ganglion and Mauthner cells of teleost fish which generate tail flick) but in tetrapod vertebrates, it appears that groups of neurons are required for pattern generation (eg. oculomotor saccade control in primates by colliculus cells). Burst neurons may be modified by synaptic currents and membrane potentials. The pyloric rhythm generator of the crustacean stomatogastric nervous system is based on the pacemaker neuron while the gastric rhythm generator system of the stomatogastric nervous system is based on network dynamics [Marder & Calabrese 1996]. The crustacean *Aplysia* pyloric rhythm is a five-phase rhythm in which the core lateral pyloric, pyloric and pyrolic dilator fire sequentially activated by the pacemaker anterior burst neuron shaped by its connections to the pyloric dilator neuron in a phased cycle of frequency 0.2-3 Hz. The gastric mill rhythm of crustaceans is based on the movement of lateral and medial teeth to grind food within their stomachs which exhibit three modes of coordination. There is no single pacemaker neuron but the rhythm is based on emergent network properties of reciprocal inhibitory connections among participating neurons – the interneuron 1, gastric mill, medial gastric, lateral gastric, dorsal gastric, anterior medial, and lateral posterior gastric neurons. The stomatogastric nervous system comprises four interconnected central pattern generator networks – esophageal rhythm (10s period), cardiac sac rhythm (30-120 s period), gastric mill rhythm (5-10 s period) and the pyloric rhythm (0.5-2s period). Their interconnections generate an overall control system with circuit switching. Central pattern generators of the spinal cord are activated by the application of different neurotransmitters, eg. N-methyl-D-aspartate (NDMA), dopamine, but require no sensory input but such sensory input can influence the characteristics of pattern generation, eg. through amplitude or frequency modulation by neurosecretory influences. Sensory stimulus can modify transduction process, alter neuron conductance or modulate transmitter release or a combination thereof. Generally, CPGs are distributed into local centres along the neuraxis (reticulospinal) of organisms, eg. control centre to control cardiac muscles in crustaceans. More complex control centres exist in stomatogastric ganglion of the lobster which controls rhythms generated by mutual inhibition connections. The lamprey might be regarded as a prototype vertebrate having evolved earlier than fish [Grillner et al 1995]. It has a brainstem and spinal cord but is primitive. The spinal network contains of pattern generators contain excitatory glutamate interneurons and inhibitory glycinergic interneurons that project to other ipilateral and contralateral neurons respectively. Furthermore there are excitatory and inhibitory sretch receptor neurons that detect the lateral bending movements during locomotion.

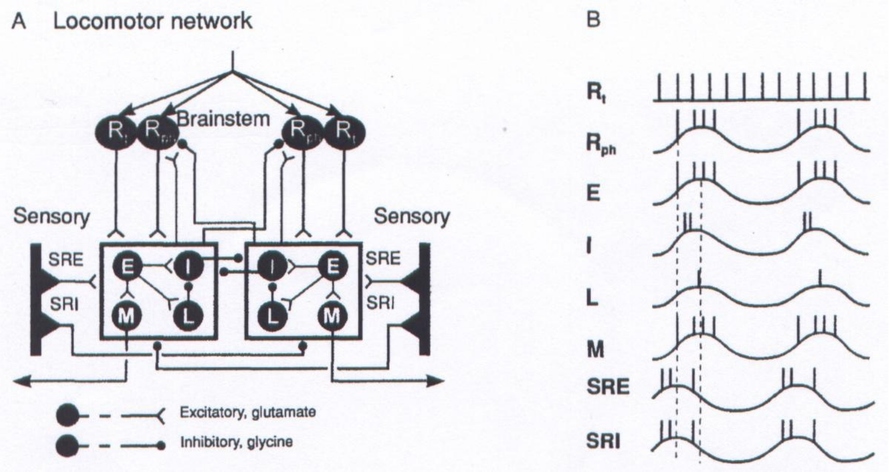


Fig 4-7 Segmental neuronal network that coordinates lamprey locomotion: brainstem, segmental and sensory components generate burst activity [from Grillner et al 1995]

The leech swimming control system is even more complex which controls 21 segments for coordinated alternate dorsal and ventral musculature. Other similarly complex motor control systems exist in the limbs of the cockroach and the flight muscles of the locust. The distribution of local centres requires timing coordination between different muscles of different body portions activated by different regions of the neuraxis. This may occur through mechanical linkages such that each centre uses local sensory information derived from other centres, eg. limb forces during locomotion are dependent on which other limbs are in contact with the ground, eg. cockroach force detectors in the limb inhibits lift-off if the applied load is too high. During locomotion, each limb is activated at a particular phase of locomotion, but if an obstacle is encountered, sensory input modifies the phasing of the limb movement. Load detectors detect the amount of force on the limb during stance phase which should be low during the latter part of the stance because the other limbs will have distributed the overall load. If however, there is a high load at the end of the stance, balance will be disrupted if lift-off is undertaken. Synchronised oscillations detected by EEG are characteristic of the human brain [MacKay 1997]. Wakeful inactivity is characterised by alpha activity within the thalamus and cerebral cortex (8-13 Hz). Delta waves (1-4 Hz) is characteristic of slow wave sleep. Locomotion and immobility prior to locomotion is accompanied by theta waves (4-9 Hz) in the hippocampus indicating long term potentiation. Mu waves (8-14 Hz) in the somatosensory cortex indicates intention to perform movement but ceases during movement. Beta waves (14-30 Hz) occurs in the sensorimotor cortex during preparation for and during movement. Gamma waves (30-80 Hz) within the visual cortex or olfactory bulb occurs due to hypervigilence. It is not clear if oscillatory motor signals serve as test probes to access peripheral systems or are used as temporal reference for coordinating motor sequences (or both).

Human walking has three characteristic properties: bipedalism from fully extended leg on contact with the ground (minimising muscle activity) and footfall characterised by heel-to-toe foot stabilisation, differentiating it from the bipedalism of birds, penguins, etc. Its motor pattern cannot be a simple reciprocal activation of flexors (during swing phase) and extensors (during stance phase) as simple phasing cannot produce human bipedal walking. There is an exchange of gravitational potential and motion kinetic energy powered by the calf muscles similar to an inverted pendulum. Ankle extension is delayed by 50-100 ms after heel contact when leg extensor activity has ceased. Bipedal walking is inherently unstable and requires sophisticated neural control systems with central pattern generators, simple monosynaptic stretch feedback of ankle exetensors augmented by peripheral feedback mechanisms which switches from stance to swing [Capaday 2002]. Switch from stance to swing transition is instigated by hip muscle spindles.

There is a linear relationship between body size and wheel-base based on a correlation coefficient of 0.8694. A three layer control system for a six legged robot comprises individual leg controllers at the lowest level for leg transfer and support, leg coordination to generate gait at the next level, and a reactive layer to select gait based on sensory data [Berns et al 1995]. It is possible to learn leg trajectories as sequences of joint angles over time through reinforcement learning [Berns et al 1997, Svinin et al 2001]. Whitaker et al's (2000) LEMUR (legged excursion mechanical utility) legged mobile robot is configured such that the four rear legs have three degrees of freedom while the front two legs have four degrees of freedom with an extra degree of freedom at the shoulder. These two legs may act as manipulators.

Snakes are highly adept at moving through confined spaces and typically employ 300 joints along their length. There are a number of different snake motions [Miller 2000]. Sidewinding is particularly suited to crumbly terrain by reducing contact area with the ground with a non-sliding locomotion on compliant surfaces. Horizontal and vertical waves of undulation travel down the snake length 90° out of phase with the horizontal amplitude around three times the vertical amplitude. It is more energetic and less stable than other forms of snake locomotion. Concertina progression involves a static curve along the length of the snake. There are two concertina gaits which are based on exploiting friction of the scales with the ground. For open ground, a straight head and tail are connected by a single S curve in the centre of the snake, the amplitude of the S changing. For narrow passages, a sinusoidal wave all along the snake's length can be altered in amplitude at different regions. Horizontal undulatory progression involves a travelling wave along the snake length using ground friction. Rectilinear motion requires the snake skin to be pulled forward over the ribs and modulation of downward pressure by muscular action. This is used in climbing and rocky terrain. Early snakebots suffered from difficulties with direct friction, especially lateral friction, between the robot and the ground, so wheels are commonly used to minimise friction. Most snakebots are modular using identical modules except at the head. One of the chief difficulties is accommodating electronics, batteries, sensors, wiring and payloads into such distributed structures. The torque on the joint motors is highest for the central portion and diminishes towards the ends. The easiest gaits to implement were horizontal undulatory progression and sidewinding. However, for practical useage, locomotion without wheels will be necessary and will require rectilinear motion and tactile sensing. NASA Ames are developing a new breed of robotic vehicle – the serpentine "snakebot" with the ability to negotiate rough terrain by going around or over obstacles. All the modular segments of the snakebot's body are identical, hinged together into a chain and each hinge is powered by a single motor, gearbox, control electronics and power source (nominally battery). The robotic serpent can burrow into loose soil, stiffen itself as a mast, act as a robotic manipulator or adopt a serpentine travelling gait to transport itself across the surface such as sidewinding, coiling or flipping. The addition of strain sensors and/or artificial skin would allow it to adopt reflexive behaviours under the overall control of a central computer "brain" which performs navigation and planning. Such serpentine snakebots are robust to component failure due to their inherent redundancy. These techniques are under development and motion control is inherently complex involving similar requirements to legged motion.

A novel form of locomotion is based on using the Martian environment as its energy source, ie. Martian wind and thermal energy. This is the Tumbleweed concept developed at the University of Helsinki inspired by the Russian Thistle. In its seed dispersal phase, it dries out and a layer of cells in the stem separates from the root. The ballast driven design uses a fluid ballast within a series of circumferential shrink-tubes filled with fluid which respond to temperature differentials. Fluid collects in hot areas generating an off-balance torque to cause the tumbleweed to roll. The lever ballast design uses a ballast mass attached to a motorised robotic arm which extends from a central spar aligned with the rolling axis. As the arm rotates about the spar, a roll moment is induced, similar to a reaction wheel.

4.1.2. Marine Locomotion

We briefly consider marine locomotion with potential application to the exploration of Europa. A variation on snake locomotion is cetacean swimming through water – such locomotion methods might be suitable for deployment on the hypothesised subsurface ocean of Europa. A propellor generates thrust by speeding up fluid flow through it from the vehicle speed v_{veh} to an output speed v_{op}. Thrust is a product of mass flow and the speed difference (v_{op}-v_{veh}). The power output is the product of thrust and the vehicle speed. The input power is the kinetic energy per unit time, ie. $P_{in} = \frac{1}{2}\dot{m}(v_{op}^2 - v_{veh}^2)$. The Froude propulsive efficiency is given by:

$$\eta = \frac{2v_{veh}}{v_{op}+v_{veh}}$$

Now, $v_{op}>v_{veh}$ so $\eta<100\%$. If $v_{op} \to v_{veh}$, a large mass flow is required for the smallest increase in speed. Hence, jet propulsion is inefficient as jets give reduced mass flow with higher output speed. However, jet propulsion is common in nature – jellyfish, dragonfly nymphs, squid, scallops, etc. This is because the ingestion of water serves also the supply food or oxygen to the body with the body acting as a valve. Many such as squid use jet propulsion for rapid evasion of predators or chasing of prey but use their fins for normal swimming. The fastest swimmers – fish and cetaceans – utilise propellor mechanisms which are oscillatory rather than rotary as in artificial flying machines. Fish locomote by either anguilloform swimming (lateral axial undulations as in eels and lamprey) or by carangiform swimming (flapping tail and/or fins). Cetaceans – porpoises, dolphins and whales – are streamlined marine mammals. Their skins are smooth on which neoprene suits are based encapsulating blubber. They have a single dorsal fin, paired forefins but no hindfins and a horizontal tail with paired fluke that generates the propulsive thrust for swimming. The odontocetes (toothed whales, eg. porpoises, dolphins, killer whales and sperm whales) have teeth and feed on large marine animals while the mysticetes (baleen whales, eg. blue whale) have horny plates that sieve plankton from the water. Oscillating flows are the basis of marine propulsion due to the formation of vortices similar to flapping flight – the main constraint in swimming animals is minimisation of drag. Indeed, fish fins employ leading edge vortices of flapping fins which is more efficient than drag-based rowing. The relevant parameters are foil geometric shape, aspect ratio, angle of attack, Reynold's number and Stokes frequency [Triantafyllou et al 2004]. Reynold's number $\mathrm{Re} = \frac{v_\infty c}{v}$ of fish assuming average chord length c of 20 cm and kinematic velocity of 0.5c/s is 20000, very different from flight. Water flow over the fins is based on Stokes frequency $S = \frac{wAl}{v}$ =18000 assuming fin beat frequency of 3 Hz and fin amplitude and length of 2 cm and 5 cm respectively.

In carangiform fish, propulsive movement is localised to the last 30-40% of fish length and are moderate in amplitude. In fact, tuna propulsion is localised to only 15-20% of its body length. For underwater vehicles, this allows the forward body to be used as a rigid compartment, eg. RoboTuna [Anderson & Kerebrock 2000]. The articulated tail structure comprises of a planar, 4 DOF robot arm which acts upon a tuna-shaped tail fin to oscillate at up to 1 Hz for a speed of 1.25 m/s. The tail exostructure cionverts the discrete movements of the arm into smooth movements of the exostructure. Rigid buoyant foam ribs within the exostructure provide this smoothing function. It includes a 6-axis inertial measurement unit of three accelerometers and three gyros, a compass, tail linkage positioon sensors, tail linkage force sensors, and a depth sensor. Its tunas-like pitch-controlled pectoral fins are located just forward of the centre of gravity and act as canards. Ayers (2000) has designed and constructed a biomimetic lobster-based robot. Electronics are housed in a plexiglass bay which forms the hull. Eight modular walking legs are attached. Anterior claw-like hydrodynamic control surfaces are controlled by a dc motor. Paired MEMS-based antennae are controlled in yaw and are used for tactile sensing for collision avoidance and water current detection based on cantilever bending. Myomorphic actuators based on shape memory alloy (NiTi) wires are controlled by PWM based recruitment of motoneurons to produce a linear graded force [Witting et al 2000]. The leg motor control system was based on neural circuits of command, coordinating and oscillator neurons. Command neuron coordinating neuron central pattern generator oscillator neuron model of motor control of locomotion is a variation on the central pattern generator model [Ayers 2000]. Command neurons provide decision-making functions for organising behaviours. Speed determines the period of leg stepping and determines recruitment level of propulsive actuators. Coordinating neurons control timing and reset of oscillators.

Oscillator neurons act as pattern generators. Steering is achieved through variation of leg elevation via synaptic inhibition. Height, pitch and roll are similarly controlled through recruitment determining individual limb depression. The states defined for the RoboLobster included: thorax pitch/roll/yaw/height, walking direction/speed, chelae pitch/yaw, antennae yaw, uropod flexure and abdominal pitch. Overall behaviour is selected from a library of action patterns invoked by sensory input.

Jellyfish are colonies of plankton (both zooplankton and phytoplankton) which drift relative to each other drifting together with the current. The largest members of plankton are copepods, tiny crustaceans related to shrimps which propel themselves at ~mm/s within water (which at the scale of ~1mm represents a high viscosity fluid). They possess several pairs of feeding appendages close to their mouths including a second, short pair of antennae. By beating these antennae and feeding appendages, copepods draw water filled with other plankton into their mouths. The circular currents generated move the body slowly forward. In addition, copepods have five swimming legs which provide brief bursts of speed when they kick backwards. Most copepods are omnivores, eg. Calanus which possesses large antennae which detect water-borne vibrations from zooplanktonic larval prey. Their attack zone, some 2-3 body lengths in range invoke attack when prey are detected within it. Cnidarians (coelenterates) – sea anemones, corals, hydroids and jellyfish - pulsate rhythmically driving the animal forward by jet propulsion. They trail a number of long tentacles behind them. Most hydroids exist in two forms – the sedentary polyp and free-swimming medusa. Medusa is the transient sexual phase of the lifecycle – mobility is important for dispersion in this phase. Jellyfish are an example where the medusa phase is the main part of the lifecycle. Most protozoans are ciliates with their surfaces covered by small hairlike processes, eg. paramecium ~20μm-2mm in size (on average 50-500μm). All ciliates move at similar speeds ~1mm/s. Cilia have roughly constant diameter of 0.25μm and beat constantly in coordinated fashion. During the power stroke, cilia are stiff, while during recovery, they are limp. Flagellates range in size ~1-50μm and locomote at ~0.1mm/s. They possess between one and four whip-like flagella, each of which has the same structure as a cilium but is much longer.

One of the most appropriate hydrostatic propulsion methods applicable to spaceflight is the use of invertebrate jet propulsion whereby a fluid-filled cavity surrounded by contractile tissue [Viadyanathan et al 2000]. Invertebrates have been classified into two maor types classified according to how the mouth is formed: protostomia (eg. annelida, mollusca, arthropoda) and deuterostomia (eg. echonodermata and tunicata). Worms, leeches, jellyfish, snails and slugs have hydrostatic skeletons to provide flexible bodies for both propulsion and accommodate irregular spaces. Muscles surrounding the fluid-filled body cavity may act circumerentially or longitudinally. Assuming a compressible cavity of cylindrical volume:

$V = \pi(r_L + r_C)^2 L_L$ where r_L=longitudinal muscle radius
r_C=circumferential muscle radius
L_L=cavity radius

Length of circumferential muscle is equal to the circumference of longitudinal muscle: $L_C = 2\pi(r_L + r_C)$. Hence, $L_C = \sqrt{\frac{4\pi V}{L_L}}$, ie. small changes in diameter yield large changes in length. When the longitudinal muscle contracts, the structure becomes short and fat, stretching the circumferential muscle. Converesely, when the circumferential myscle contracts, the cavity elongates and thins. Muscular forces are related by: $F_L = F_C \sqrt{\frac{\pi V}{L_L^3}}$. Locomotion is by alternating segment contraction/elongation and undulation by alternate contractoon of groups of longitudinal muscles. Step size for n segments, $S = n(L_{rest} - L_{contract})$. Differential contraction causes the structure to form an arc that bends at angle θ in the direction of contraction:

$S = nL_{rest} - L_{chord}$ where L_{chord}=chord length of bend at contraction

$$= L_{contract} \frac{\sin(n\theta).\cos(\frac{1}{2}\theta)}{\cos(\frac{1}{2}n\theta).\sin\theta}$$

Shape memory alloy wires were used as the actuation system for a robotic worm due to their ability to work underwater, their controllability, their dynamic and force amplification properties, and their versatility of deployment as wire bundles, springs, etc. Each hydrostatic element comprises four SMA tension springs attached to two end disks of pine wood sandwiching a badder filled with fluid. Heating altered the spring cionstants from k_{cold}=105 N/m to k_{hot}=200 N/m. Compressional longitudinal force extered by the SMA springs against the bladder, $F_{lc} = 4K_h(L_{rest} - L_{contract})$. The longitudinal restorative force is given by: $F_{lr} = 4K_c(L_{rest} - L_{contract})$.

Swimming in lampreys and leeches are based on travelling wave of body undulation at a single wavelength independent of speed. Sensory feedback from stretch receptor to generate phased motor bursts from the body enables intersegmental phase lags to be established with constant phase differences. This is enabled through reciprocal inhibitory connection through the midline modified by sensory feedback.

4.1.3. Aerial Locomotion

Flight in the biological world may be exemplified by birds. Most aircraft obtain lift from fixed wings and forward propulsion from jets or propellers. This separation of lift and forward motion is unknown in nature where lift and propulsion are obtained by steering a single thrust source (wings). The helicopter is an exception with its integrated propulsion/lift system. Fixed wing vehicles dynamics are determined by their large size – wing lift is dependent on area while its weight varies with volume. To obtain high lift, an aircraft must have large area wings or fly faster – faster vehicle speed implies faster velocity output for forward thrust. The fixed wing aircraft converts some of the high speed, low volume thrust into low speed, high volume downward flow for lift. Birds are much slower than aircraft – the maximum forward speed for a bird is around 30 m/s. As birds get larger, their wing loading increases as their weight increases faster than their wing area. At a certain size, flapping flight can no longer sustain flight due to energy limitations. However, soaring extracts energy from the environment rather than the muscles, particularly exploited in rising thermals. In order to track such narrow thermals, soaring birds tend to have slower flight speed to enable them to manoeuvre quickly. Hence, they have broad wings, eg. raptors. Commercial jets fly at Reynolds numbers ~10^7 compared with birds and insects which fly at Reynolds numbers ~10^4 and 10^2 respectively. Early insects had two pairs of wings (eg. Protodonata) but most modern insects have lost one pair or the two wings are coupled into single surfaces. The smallest flying insects are of mass 20-30 μg (Re~10) while the largest are 2-3g (Re~5000-10000). In general, wing area $A \propto m^{2/3}$ and wingbeat frequency $f \propto m^{-1/4}$ where m=mass. Micro-air vehicles generate thrust through wing flapping. Blade element theory of propellers suggest that the force components for a flapping wing are:

$L = \frac{1}{2}\rho c v_r^2 C_L$ normal to relative velocity where c=wing chord

C_L=0.6-0.9 for most insects wings

$D = \frac{1}{2}\rho c v_r^2 C_D$ parallel to relative velocity

The conventional aerodynamic approach is insufficient to model biological flight. Sinusoidal flapping $z(t) = h\sin(kt)$ generates induced velocity –z'(t) to give an effective velocity v_{eff} at an angle of attack with respect to the chordline α where $k = 2\pi fc / V_\infty$ where V_∞=free-stream velocity. However, this simple Knoller-Betz interpretation does not account for the shedding of vortices from the airfoil trailing edge on the plunge which corresponds to a continuous change in incidence angle of the wing. Indeed, insect wings produce two-three times more lift than can be accounted for by conventional aerodynamics. A strong dynamic stall vortex forms at the leading edge which propagates over the upper surface downstream past the trailing edge. The leading edge vortex remains stably attached to the wing and does not shed in flapping wings enabling hovering [Sane 2003].

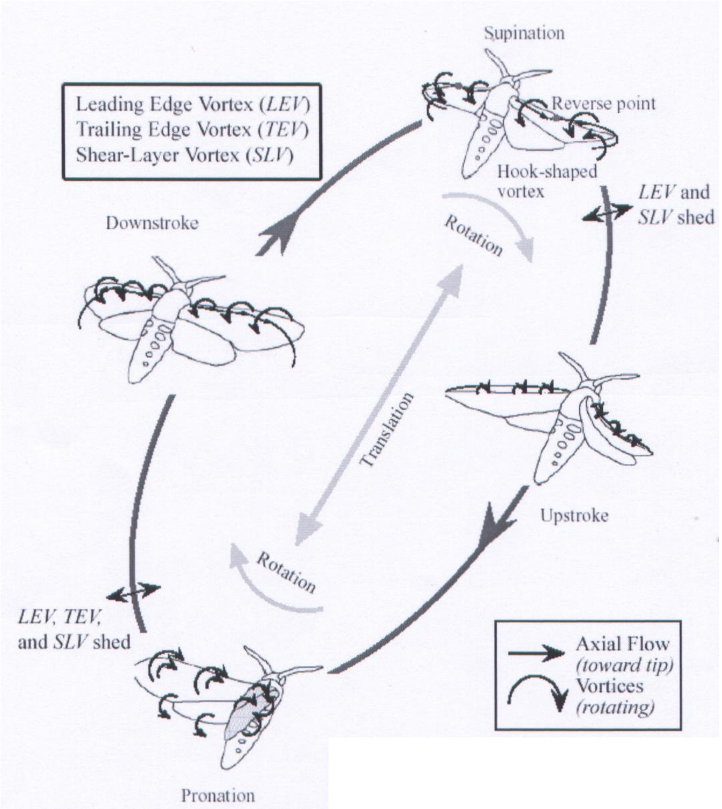


Fig 4-8 Formation and dissipation of leading edge vortices, trailing edge vortices and axial flow during flapping cycle [from Sane 2003]

The resultant dynamic lift is much greater than the static lift due to the incidence angle. Fluid motion around an insect wing is described by the incompressible Navier-Stokes equation:

$\frac{\partial v}{\partial t} + (v.\nabla)v = -\nabla P + \frac{1}{\mathrm{Re}}\nabla^2 v$ where v=velocity of flapping wing relative to fluid

P=pressure

$\mathrm{Re} = \frac{\rho V_\infty L}{\eta} = \frac{4\phi f L^2}{\eta AR}$ =Reynold number $\propto m^{0.42}$

ρ=fluid density

V_∞=fluid velocity

L=wing length

η=dynamic viscosity

ϕ=wingbeat amplitude
f=wingbeat frequency
AR=aspect ratio

Reynolds number has low value during laminar flow (high viscosity) and high value during turbulent flow (low viscosity). For experimental work, fluid pressure is difficult to measure, so the curl eliminates the pressure term:

$\frac{\partial w}{\partial t} = \nabla \times (v \times w) + \frac{1}{\mathrm{Re}} \nabla^2 w$ where $w = \nabla \times v$ =vorticity

For inviscid (negligible viscosity) flows, w=0, then $v = \nabla \phi$ where ϕ=potential of velocity field. Stokes theorem relates area integral of normal to vorticity to line intrgal of velocity around a closed contour Σ bounding a surface S:

Circulation, $\Gamma = \oint_{\Sigma} v.dl = \int\int w.n.dS$ where n=normal vector

The Kutta-Jukowski theory of thin films states that any shear generates lift perpendicular to the inclined wing and viscous drag parallel to the wing. For inviscid steady-velocity flows,

Lift, L=$\oint_{\Sigma} u.dl = k$ - Kelvin's law which states that total circulation (vorticity) is zero.

Boundary layer defines transition from zero velocity flow at surface and free stream velocity – the thickness of the boundary layer depends on Re. High Reynolds number defines negligible viscosity and is characteristic of large flying animals with inviscid flows, this is not necessarily the case for most insects which fly in low Reynolds number regimes. However, rapid changes in wing velocity during flight prevent thick viscous boundary layers from forming, raising the local Re number. During hovering, downstroke and upstroke are almost symmetrical to provide weight support. As flight speed increases however, downstroke dominates with a longer path. Vortex models approximate flapping wings to propellor blades – the flapping motion is approximately restricted to a stroke plane which lies to a near constant orientation ~40^{o} with respect to the horizontal. Wings are also twisted by 10-20^{o} along wing with higher angle of attack at the wingbase than the tip. The Weiss-Fogh clap-and-flap mechanism accounts for the high lift in wing flapping. The clap occurs when the wings touch dorsally before pronation at the start of the downstroke. The leading edges touch each other before the trailing edges causing vorticity losses and increased lift and thrust. The leading edges fling apart causing increased circulation. As the wing increases its angle of attack, leading edge vortex forms above the wing generating lift through Polhemus leading edge suction effect of dynamic stall. During the downstroke, air swirls around the leading edge and rolls up into a leading edge vortex which enhances lift. This is dynamic lift at high angle of attack briefly generating extra lift before stalling. Spanwise flow causes the leading edge vortex to spiral to the wing tip to stabilise attachment of the leading edge vortex to the wing [Ellington 1999]. This convection of vorticity to the wingtip prevents the leading edge vortex from growing too large and causing a deep stall. Close to the end of each stroke, insect wings undergo significant pronation and supination about the spanwise axis to maintain a positive angle of attack to ensure lift during both forward and reverse strokes. Effective angle of attack relative to the wingtip path is approximately constant at 30^{o} during downstroke. Thus the wing rotates through 120^{o} so that the leading edge always leads. Variations in the timing of these rotations and tilting of the stroke plane gives manoeuvring. Tilting the stroke plane is a simple mode of flight control. As the wing reverses stroke, it sheds both leading and trailing edge vortices – this generates wake capture.

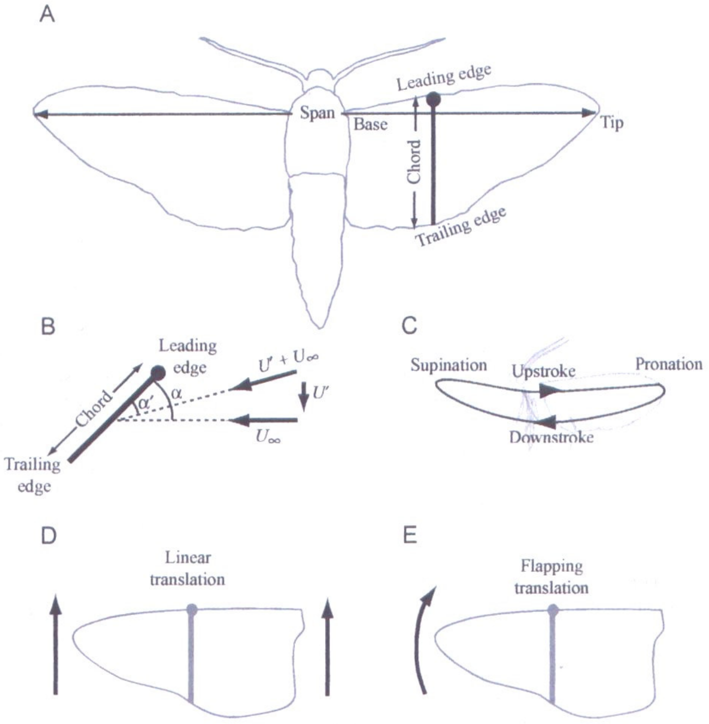


Fig 4-8 Insect flight aerodynamics [from Sane 2003]

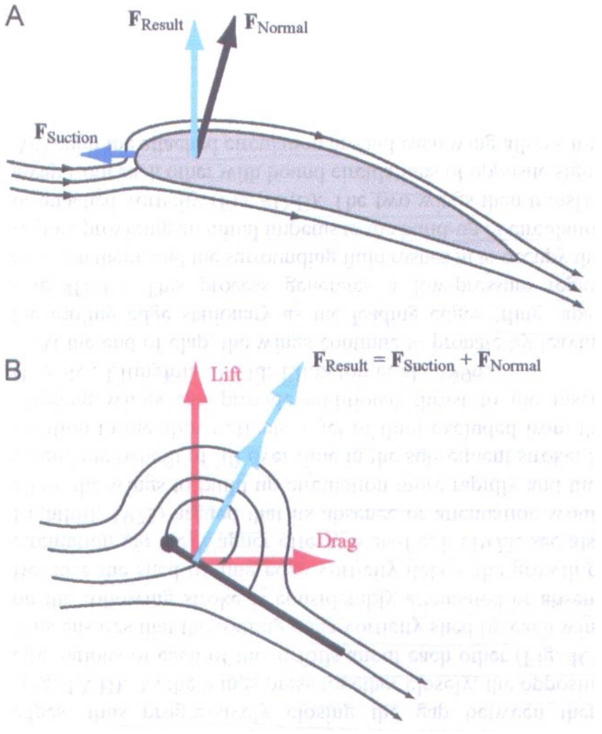


Fig 4-9 Polhemus leading edge suction theory [from Sane 2003]

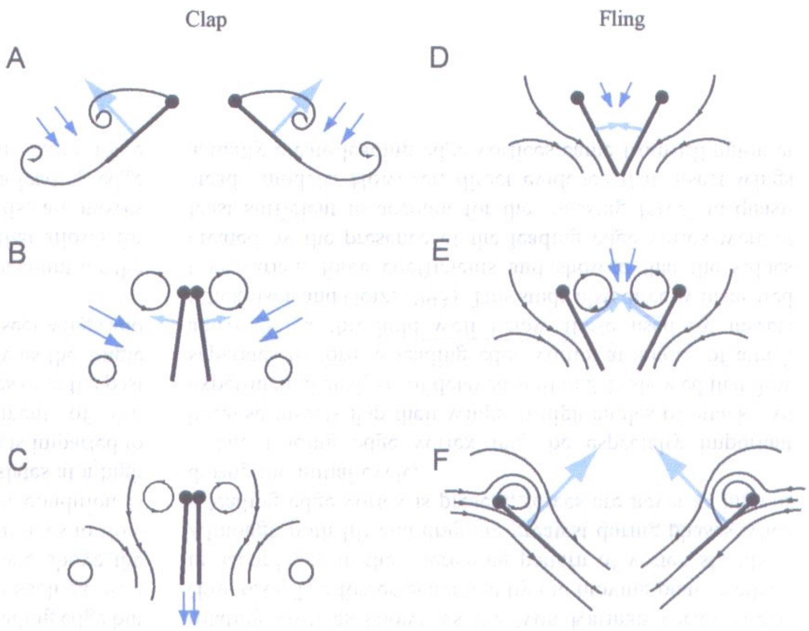


Fig 4-10 Leading and trailing edges as wings approaching each other to clap (A-C0 and flinging apart (D-F) [from Sane 2003]

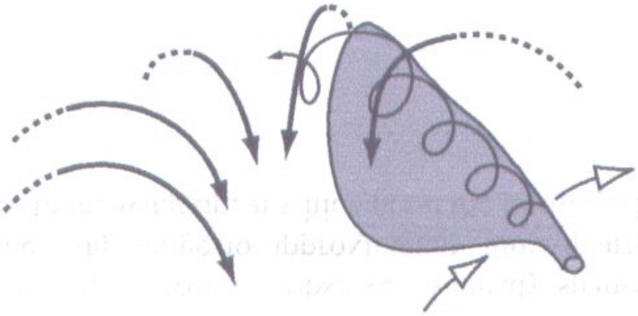


Fig 4-11 Stable attachment of leading edge vortex [from Sane 2003]

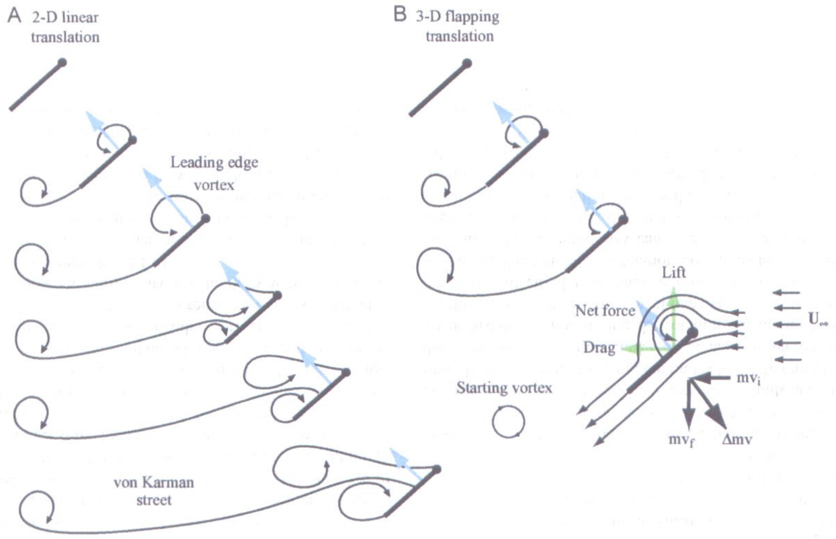


Fig 4-12 (a) linear 2D translation of aerofoil; (b) 3D flapping translation of aerofoil [from sane 2003]

	Mass (g)	Wing length (mm)	Wingbeat frequency (Hz)	Wingbeat amplitude (°)	Wingloading (N/m²)
Bumblebee	0.175	13.2	149	114	36
Hawkmoth	1.6-2.0	51	25-26	115-120	9
Parasite wasp	0.025	1.5	400		

For comparative analysis, advance ratio may be defined as:

$J = \frac{V}{2\Phi fl}$ where V=flight velocity

Φ=wingbeat amplitude
f=wingbeat frequency
l=wing length

Advance ratio fixes wingbeat amplitude and frequency so stroke pane angle controls inclination of downstroke path and net vertical aerodynamic force. Most insects have J=0.6-0.9, with maximum J~1 which determines maximum flight speed for a given flapping frequency. Any micro-air vehicle must have independent control of flapping amplitude and flapping angle to ensure optimal angle of attack and performance at different speeds and for maneouvring. Reversible wing twist between base and tip provides deformable aerofoils. Insect flight acts as a damped resonator so wingbeat frequency is approximately constant. Stiffness of the thorax can be altered to provide some variation in resonant frequency. Quality of an oscillator is defined as:

Q=2π (peak oscillator KE/energy dissipated per cycle)

Eg. Q_{fruitfly} =6.5, Q_{hawkmoth} =10, $Q_{\text{bumblebee}}$ =19.

Mass supported during hivering with a horizontal stroke plane, $m = 0.387\frac{\Phi^2 f^2 l^4 C_L}{AR}$

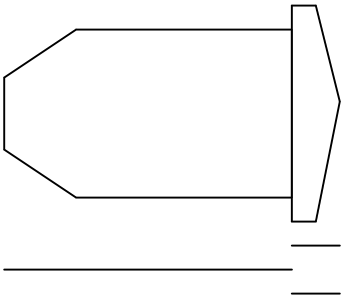
Specific induced jet power required to support mass, $P_{ind} = 14.0\, fl\left(\frac{\Phi C_L}{AR}\right)^{1/2}$ (W/kg)

Specific power required to overcome drag, $P_{drag} = 18.2\Phi fl\,\frac{C_D}{C_L}$

Total power required, $P = P_{ind} + P_{drag}$

Typically for insects, $\Phi=120^{o}$, AR=5-12 (av. 7), $C_L \leq 2$-3, $C_D = 7\,\mathrm{Re}^{-1/2}$, $\frac{C_L}{C_D} = \cot\alpha$, $\alpha=30^{o}$, giving $P_{drag} = 10.5\Phi fl$ and $P = 32.8 fl$.

An efficient micro-air vehicle has been developed by Jones & Platzer (2002). The vehicle is a large wing providing most of the lift while two small wings at the rear arranged in biplane fashion provide propulsion. The two aft wings flap in counterphase at a fixed amplitude with a maximum frequency of 25 Hz. Evidently, increasing wing length l is the most efficient way to increase lift capacity due to the l^4 dependence. Aerodynamic power also favours increasing wing length rather than flapping frequency at the expense of reduced flight speed.



Flapping flight offers a manoeuvrability beyond that available from rotary winged aircraft which in insects can generate up to 10 m/s² and impart 100 W/kg of specific power to the wings.

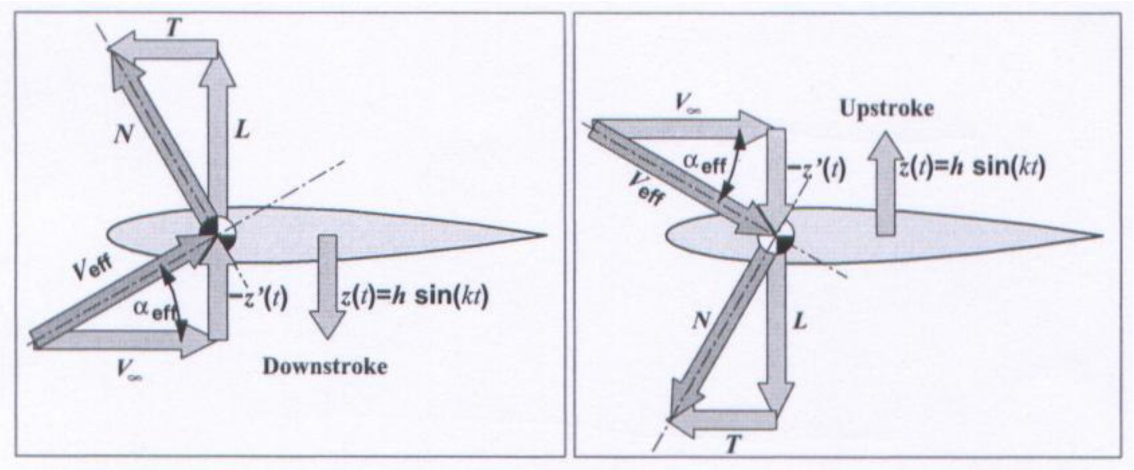


Fig 4-13 Thrust production during flapping flight

RoboFly is a microrobotic flapping flyer with a 25 mm wingspan of dual wings driven by two piezoelectric actuators per wing based on a four-bar geometry inspired by the blowfly [Fearing et al 2000]. The blowfly has a mass m of 0.1g, wing length l of 10 mm, wingbeat frequency w of 150 Hz and a wingstroke angle 2θ of 70°. The net wing lift must at least exceed the insect weight of 1 mN. A pair of strain gauges on top and side wing surfaces of RoboFly measure lift and drag. The wing damping is defined by:

$b = \frac{2mgl}{w\theta}$ =13 nNsm

RoboFly flaps at 16 Hz in an oil medium to give an equivalent Reynolds number as a fruitfly flapping at 220 Hz in air:

$\mathrm{Re} = \frac{Sf\phi}{v}$ where v=viscosity of air =1.6 x 10^{-4} m^2/s
S=wing surface area=32 cm^2
ϕ=stroke amplitude=1 rad
=340

The thorax four bar frames require high stiffness modelled as cantilever beams:

$k = \frac{3EI}{l^3}$ where $I = \frac{wh^3}{36}$ for a triangular beam
h=beam height
w=beam width
l=beam length

Peak wing speeds reached 2m/s. The Q ratio of a resonant system (defined as the ratio of stored energy to dissipated energy) for a blowfly is low ~1-3 (nominally 2.5) for high manoeuvrability which defines wing inertia: $I_w = \frac{Qb}{w}$ =3.3 x 10^{-11} kgm^2. The wing actuator must resonate at w with stiffness: $k_w = I_w w$ =30 μNm. Actuator displacement is given by:

$\theta_a = \frac{\theta_w}{nQ}$ where n=transmission ratio, θ_w=wing displacement

Actuator torque is given by: $\tau_a = K_a \theta_a$

There are three mechanisms for flight in insects – delayed stall, wake capture and rotational motion.

Control of flight is different to that in walking locomotion. Muscles move the wing indirectly by rhythmically deforming the thorax. Dorsolongitudinal muscle contraction bends the tergum upwards to generate downward flap of the wings about the wing hinges. Dorsoventral muscle contraction generate upward flapping. There are two types insect fliers – neurogenic fliers with wingbeat frequencies of 15-35 Hz (eg. locust) and myogenic fliers with wingbeat frequencies of 30-1000 Hz (eg. flies) [Wendler 2000].

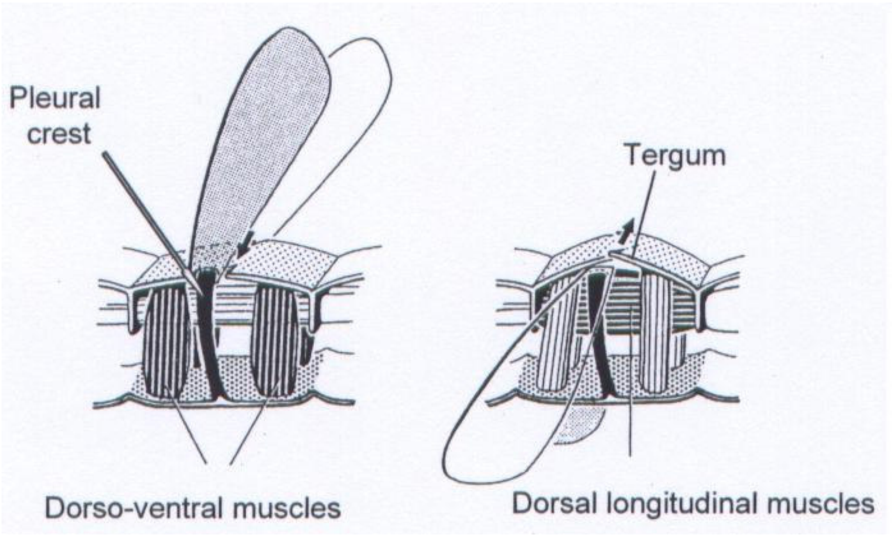


Fig 4-14 Flight power muscles on wing and control of muscle contraction [from Wendler 2002]

In neurogenic flight, wingbeat is under full neural control which always generates maximal muscle contraction and control is enabled through phase changes of neural firing controlled by receptors.

Often power and steering utilise the same muscles controlled phasing. Myogenic fliers exploit stretch activation of muscles which induces strong contraction to enable rapid mechanical oscillation with fewer neural firings (less than wingbeat frequency). Steering typically uses different muscles to propulsion. In both cases, the wing frequency response is maximum at 15 Hz which matches the mechanical resonant frequency of the thorax. Wendler (2000) has subjected the hawkmoth to direct computer control by removing its ventral nerve cord and substituting computer-generated pulses to control its power muscles.

Michelson & Naqvi (2003) recommend that air vehicle design should be bio-inspired rather than biomimetic – biological systems are often limited, can be difficult to replicate, and can be exceeded by technology. The largest flying creatures are the albatross and condor which are soaring birds – all bird species larger than 13 kg are flightless limited by muscle fibre contraction capacity of 300-400 kN/m^2 which scales with square of cross section. There are 10 principles for the design of robotic air vehicles:

(i) Biomimetics is a good starting point
(ii) Pure biomimetic approaches can yield non-optimal performance solutions
(iii) Sometimes optimal solutions result from traditional technology
(iv) Biomimetic solutions may not be practical
(v) Wingbeat requires sufficient power – artificial muscles have yet to demonstrate sufficient efficiency to lift vehicles
(vi) Biomimetic flapping is complex to control involving complex muscle structures and resilin energy storage
(vii) Flight stability control is complex involving flap angle, span, rate and wing anfle of attack modulation
(viii) Poor integration generates mass creep requiring extensive use of m,ultifunctional structures, eg. 50g entomopter
(ix) Designs must capitalise on resonance in storing energy within their structures which comprises ~35-85% of elastic energy storage compared with 10% efficiency for muscles
(x) Average power density for current battery technology is marginal for small scale flapping wing flight

Flapping velocity varies from zero at the extremes to a maximum at centre of motion:

$v = r\frac{d\beta}{dt}$ where r=span location

β=flap angle

Around 80% of lift is produced in the downstroke primarily due to the leading edge vortex. The entomopter is powered by a chemically fuelled reciprocating chemical muscle which offers 70 Hz reciprocation rates. The regenerative muscle consumes chemical fuel non-combustively. Waste gas is used to generate circulation-controlled lift.

The Entomopter is multimode robot capable of flapping flight, ambulation and swimming powered anaerobically by a reciprocating chemical muscle system is a candidate for Mars exploration as a low Reynold's number 50g 20 cm wingspan flier running on 4W of continuous power. The wing aerodynamics are based on the hawkmoth *Manduca Sexta* X-wing flapping but rather than utilising active modulation of wing twist angle of attack, pneumatically controlled airflow (waste products from the reciprocating chemical muscle) over the wing through hollow ribs along the trailing edges is adopted increasing lift by 500%. Furthermore, rather than using clapping wing flapping, the X wing fore and aft wings pivot like seesaws about the central fuselage 180^o out of phase of each other. A simple resonant wing beat provides roll, pitch, yaw and forward motion control. The fuselage acts as a torsional spring with a resonant frequency equal to the flapping rate. The torsional resonance of the structure stores potential energy similar to resilin in insects – indeed, insect muscles expand/contract only 2% of their lengths with up to 85% of flapping energy stored elastically. The reciprocating chemical muscle operates by catalytic combustion and is regeneratively powered from chemical fuel sources and allows 70 Hz flapping rates.

For wide-area exploration, aerial vehicles are the obvious choice. In thin atmosphere environments, winged vehicles are possible with relatively large wings and high speeds. Propellor driven aircraft have flight power of $P = 10.9\left(\frac{g}{g_{Earth}}\right)m^{0.9}v^{0.8}$. Thick atmosphere environments such as Titan lend themselves to such exploration, particularly due to its thick, hazy atmosphere which obscures its surface from orbiters. Titan's environment is dominated by ethane It is expected that organic material and water ice may have collected on Titan's surface due to impacting comets. Balloons such from lack of controllability in wind and a lack of surface pressure on landing. Airships have propulsive power of $P = 1.5\left(\frac{\rho}{\rho_{Earth}}\right)^{0.33} m^{.6}v^{1.85}$. Titan's high density atmosphere and low gravity favours the use of helicopters which like biomimetic systems combines propulsive thrust with lift. Helicopters have a hover power of $P = \frac{(mg)^{1.5}}{(2\rho A)^{0.5}}$ where A=rotor disk area; drive power is typically twice hover power. A 100 kg helicopter requires 500W of power, some 1/38 that required on Earth. Plutonium-based radioisotope thermoelectric generators based on alkali metal converters (AMTEC) are 15% efficient and 7 kg of Pu would be required to generate 500 W. Additional devices such as gyroscopes, odometry, and cameras would be required for navigation. Expendable drop-sondes may be released on landing before deployment to other sites. A novel MEMS based rotary fan has been developed which uses a scratch drive actuator rotary motor with forward and reverse control at speeds of up to 180 rpm powered by a sinusoidal AC signal [Lindeman et al 2002]. The fan blades are rotated to a specific angle-of-atack using gold coated polysilicon bimorph structures with application to micro-air vehicles operating in low Reynolds number environments by virtue of its compact, lightweight design. The SDA motor is compact and may be arrayed to produce significant output forces, superior to that offered by larger thermal and comb drive actuators. The SDA bushing scratches forward when the actuator is electrostatically deflected against the dielectric layer. The bushing pulls the actuator forward in a single step which can be repeated at a frequency of 15 kHz in air (limited by the film damping effects between the SDA plate and the dielectric layer. The motor has a sliding contact around the outer perimeter that allows charge to flow into the SDA array. The fan blade array was flip chip assembled to the motor by means of a sandwiched epoxy glued gasket insulator.

4.2. MANIPULATION SYSTEMS

Many animals possess sophisticated manipulation capabilities. The chameleon – lizards adapted to arboreal lifestyle – has fingers and toes which are opposable for grasping and a tail which is prehensile. Its tongue, which it uses for catching prey up to 35 cm away, can reach a top speed of 21 km/h within an interval of only 20 ms, ie. an acceleration rate of 486 m/s^2. Arachnids possess 8 legs but many spiders possess in addition a pair of appendages – pedipalps - behind the biting parts for handling prey. Forelimb movement control including the capacity for reaching for objects has its heritage in tetrapod evolution and represents an evolutionary adaptation for food handling behaviour [Iwaniuk & Whishaw 2000]. Other species capable of skilled forelimb movement include frogs, marsupials, dinosaurs, rodents, and primates and thus has a vertebrate lineage derived from scooping of food from which wiping, digging and locomotive behaviours are derivative. Animals lacking a corticospinal tract are capable of skilled forelimb behaviour, eg. frogs. Tetrapods exploit the rubrospinal tract which is present in all tetrapods which in mammals is required for coordinating skilled forelimb movement. Catching is a complex skill involving both spatial and temporal prediction. The hand is aimed at the location where it will meet the object rather than where the object is seen. In grasping the object, the fingers and hand are shaped in advance to ensure catching and holding the object in the hand. Time to contact with the object is defined as the ratio between the distance to contact and the object velocity. Where a target is moving at constant velocity, tau predicts the time to contact and is defined as the inverse of the rate of dilation of the image of the approaching object on the retina. If the object is accelerating, tau slightly overestimates the time to contact. This overestimation increases as the time to contact increases. This suggests the existence of motor programs organised in a hierarchical manner.

Delays in sensorimotor feedback loops suggest that reaching movements are under pre-programmed feedforward control with sensory feedback occurring only at the end of the trajectory. The minimum delay for visual or proprioceptive signals to influence movement is 80-100 ms while the duration of visually-directed movement is typically 300-700 ms. Inverse models model the inertial and viscous properties of the arm to estimate the motor commands to produce the desired displacement. Corrective commands may then be issued. A motor plan is constructed prior to movement but it appears that this plan is updated by internal feedback loops continuously which rely on a forward model that integrates sensory inflow and motor outflow to assess the consequences of the motor commands sent to the arm [Desmurget & Grafton 2000].

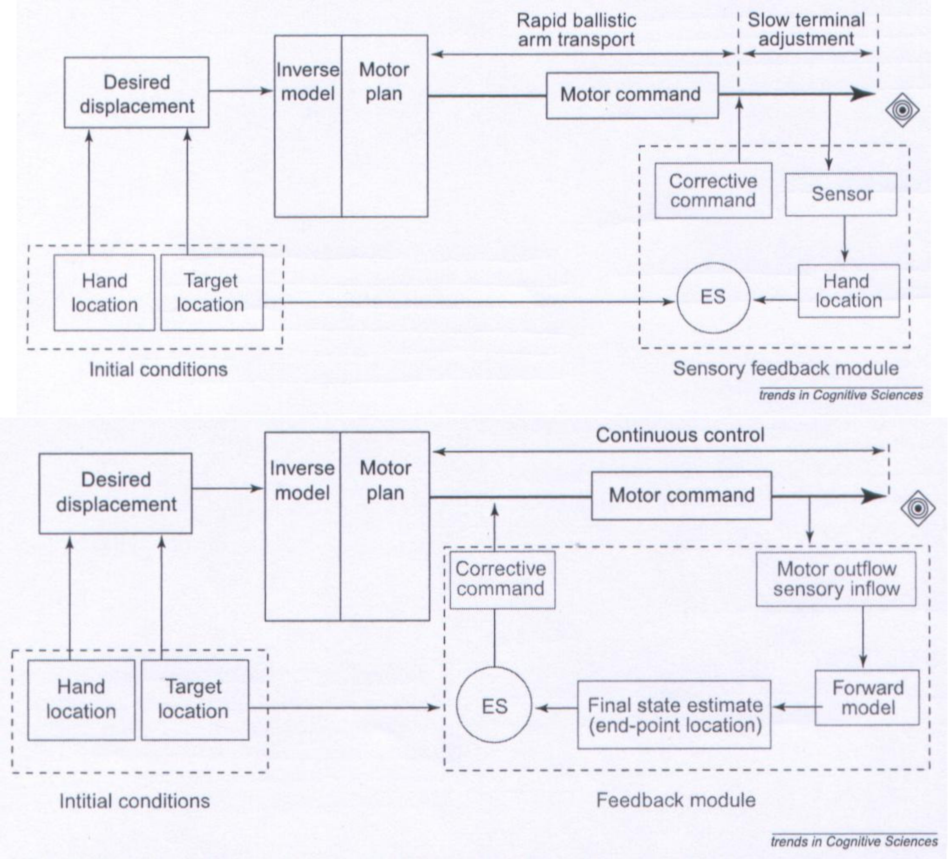


Fig 4-15 (a) classical dual model of movement control; (b) hybrid model of movement control with forward model of arm dynamics [from Desmurget & Grafton 2000]

A copy of the motor command is used in an internal feedback loop to input to the forward model this copy of the efferent command. A forward model predicts the behaviour of the motor system in response to commands and so estimate the current and future state of the end effector which may be compared to the target location without sensory feedback. This allows probable position and velocity to the hand to be estimated with negligible delays. However, augmentation with delayed sensory feedback effectively implements a Smith predictor whereby the forward prediction is delayed by the sensory delay period to compare predicted and sensory estimates. Error from this comparison may be used to update the current forward model. The primary sites for this forward model lie in the posterior parietal cortex which computes motor errors and the cerebellum which implements both forward and inverse models.

The US Robonaut (Robotic Astronaut) project is an anthropomorphic design for EVA-equivalence to overcome the limitations on the ISS SSRMS and SPDM which require special alignment and grapple fixtures. They are also too large to fit through EVA access doors and suffer from limited dexterity for complex manipulations [Aldridge 1999]. Robonaut has a similar size to an EVA-suited astronaut comprising of three 7 degree of freedom arms, each with 12 degree of freedom multifingered hands, a 6 degree of freedom stinger tail, a 4 degree of freedom binocular stereo camera platform, all mounted onto a torso with a 3 degree of freedom head (ie. pan, tilt and verge). The robotic hands are designed to handle EVA tools including power tools with human-like dexterity. The stinger tail fixes into worksite interface sockets located around the ISS for stabilisation. It can also be fitted as an end tool to the SSRMS. Robonaut will be teleoperated by an ISS astronaut (intravehicular activity, IVA) utilising telepresence technology such as head-mounted display helmet and virtual reality gloves specifically developed (Dextrous Anthropomorphic Robot Testbed, DART). The dextrous hand has 4 fingers and a thumb arranged in a human opposition arrangement. The thumb, index and middle fingers have 3 degrees of freedom while the other two fingers each have one degree of freedom. The hand also has a palm degree of freedom to enable flexing of the whole hand for grasping. Six axis force/torque sensors will be placed at the wrist and the shoulder. The hand is connected to the arm with a pitch-yaw wrist. The hand/wrist module contains 14 motors and 42 sensors. The arm has a 0.7m reach equivalent to that of the human arm with a roll-pitch-roll-pitch-roll-pitch-yaw configuration with elbow self-motion for collision avoidance. The total system has 48 degrees of freedom. Robonaut has some 150 or so sensors per arm. The design philosophy of Robonaut is EVA-equivalence and the ability to use human tooling like the EVA toolkit. To minimise the wiring harness, electronics have been embedded into the mechanisms.

Kawato et al (1988) suggested that robot control algorithms are precisely the computations that are carried out neurally in the human brain in voluntary movement and this provides an illustrative example of the robot control algorithm as a whole. Action sequences may be learned and stored in procedural memory which can then be combined into new sequences to achieve new goals. Procedural memory resides within the cerebellum and basal ganglia. Procedural skill also may provide the basis for intelligence, logical thought and language. Loop circuits in the basal ganglia for motivational reward evaluation and in the cerebellum for processing of coordinated timing are implicated in such motor learning [Hikosaka et al 1999].

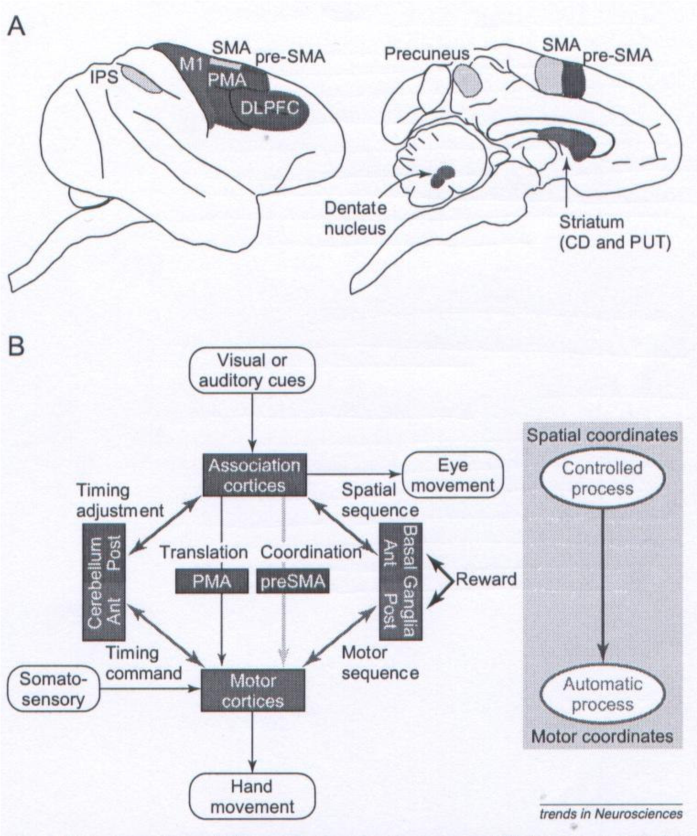


Fig 4-16 Neural correlates of parallel learning – association areas of prefrontal cortex and anterior basal ganglia comprise loop circuit that operates as spatial sequencing mechanism, motor cortices and mid basal ganglia comprises loop circuit that operates motor sequencing mechanism, anterior and posterior cerebellum contribute to motor and spatial sequencing by forming loop circuits with motor and association cortices [from Hikosaka et al 1999]

Sequential procedures are acquired independently by two cortical systems, one using spatial (Cartesian) coordinates (prefrontal/parietal cortex and the caudate of the basal ganglia) and the other using motor (joint angle) coordinates (premotor-motor cortex and putamen of the basal ganglia). They are active during the early (predominantly spatial) and later (predominantly motor) stages of learning respectively. Coordinate transformation from visual spatial coordinates to motor coordinates occurs between the parietal and premotor cortices. Correct performance relies on the serial sensorimotor information flow from the association cortex to the motor cortex through the premotor cortex. Areas 2,5 and 7 of the sensory-association cortex perform coordinate transformation from the desired joint angles θ^d and the generation of motor commands τ with the actual movements θ fed back to the motor cortex by proprioception. Sensorimotor integration shifts positional frames of reference in spatial coordinates to derive the muscular trajectories. Area 2 produces motor torque commands while areas 5 and 7 provide the cartesian trajectory and their transformation into joint coordinates. The parietal-association cortex receives visual and sensory information about the world. Neural circuits are capable of computing the nonlinear transformation and the inverse dynamics model of the musculoskeletal system through motor learning of inverse dynamics reference models in the cerebellum, ie. stimulus-response associations. This motor learning provides a nonlinear mapping between the torque input τ and the trajectory output θ^d by cross-correlation. To control voluntary movements, there are three computational problems [Kawato et al 1987]:

(i) determination of the desired trajectory in visual task coordinates
(ii) transformation these trajectory coordinates into body muscle coordinates in order to utilise proprioceptive feedback
(iii) generation of motor torque commands to realise the desired trajectory

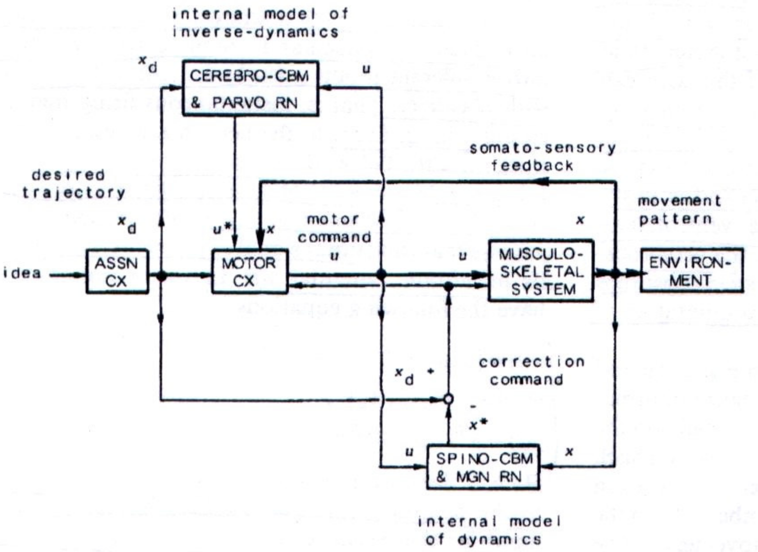


Fig 4-17 Hierarchical neural network model for control and learning of voluntary movement of three parts: main descending transcortical pathway, spinocerebellum-magnocerellular red nucleus system model acts as internal neural model of musculoskeletal forward dynamics, and cerebrocerebellar-parvocellular nucleus acts as internal neural model of musculoskeletal inverse dynamics [from Kawato et 1987]

The association cortex provides the motor cortex with the desired trajectory x^d in body coordinates. The motor command τ is computed in the motor cortex through long loop sensory feedback and transmitted to the muscles through the spinal motoneurons. The musculoskeletal system interacts with its environment to generate a trajectory x. The generated trajectory x (muscle length) and derivative $\dot{x}$ are measured by proprioeptors and returned to the motor cortex which performs error computation ($x^d - x$) with a feedback delay of 40-60 ms. The spinocerebellar-magnocelular red nucleus system receives x as input from proprioceptors and motor command τ from the motor cortex. Within the spinocerebellar-magnocellular red nucleus system, an internal neural model of the dynamics of the musculoskeletal system is constructed while monitoring the motor command τ and sensory feedback from movement x. This provides an approximate prediction x* of the movement. Internal feedback updates the motor command using this dynamic model to predict the error in movement ($x^d - x^*$). This is transmitted to the motor cortex and the muscles through the rubrospinal tract as a feedforward approximation with a time delay of 10-20 ms. The spinocerebellar-magnocellular red nucleus updates the motor command by predicting the error in movement. The cerebrocerebellar-parvocellular red nucleus receives input from the cerebral cortex but not sensory input. It monitors both the desired trajectory x^d and motor command τ to build an inverse dynamics model. Within the cerebrocerebellar-parvocellular red nucleus system, an inverse dynamics model of the musculo-skeletal system is constructed while monitoring the desired trajectory and the motor command. Both forward dynamics and inverse dynamics models are acquired during control of movements. The inverse dynamics model can compute an accurate motor command τ^* from the desired trajectory x^d which is transmitted to the motor cortex through the ventrolateral nucleus of the thalamus. The total torque is the sum of feedforward and feedback torques. As motor learning proceeds, the inverse dynamics model replaces external feedback as the main control system. This may be modelled as:

$$T\frac{dw(t)}{dt} = x(t)s(t) = x(t)[z(t) - x(t)^T w(t)]$$

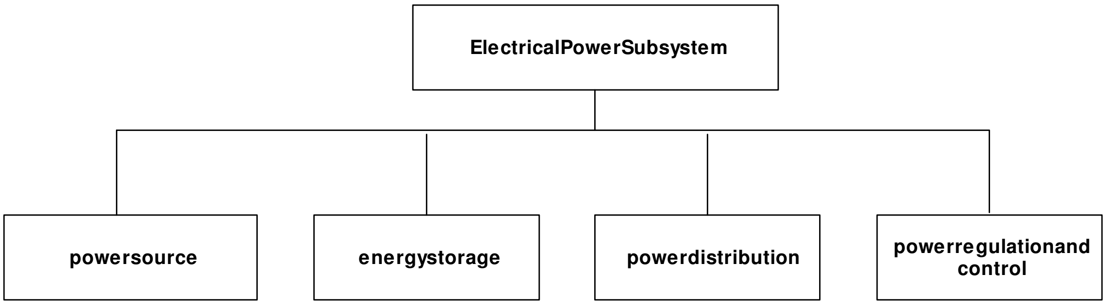
where s(t)=error signal from climbing input for Purkinje cell=z(t)-y(t)
$y(t)=x(t)^T w$=membrane potential output
x(t)=neural input
w=synaptic weight
T=time constant of synaptic weight change

Kawato et al (1988) stated that minimisation of torque change (ie. jerk) through the minimisation of an objective function is performed internally in the human brain and it has the form: $C_T = \int_{t_0}^{t_f} \sum_{i=1}^{n} \left(\frac{d\tau_i}{dt}\right)^2 .dt$. This is a nonlinear optimisation problem that indirectly minimises energy and produces a bell-shaped speed profile. There is some evidence for straight line linear path planning in human cognition in the parietal cortex [Shepard 1984]. Surface optical information about bodies is constrained by the geometric lines of perspective. Similarly, the relative motion of rigid objects are also constrained by kinematic geometry. Although an infinite number of paths exist through which an object may be moved and/or rotated from a position A to a position B, the simplest motion is given through Chasles theorem. A unique axis exists such that an object may be moved from A to B by a rotation about that axis with a simultaneous translation along that axis to generate a minimal 6 degree of freedom helical twist in 3D space (including the limiting cases of circular or rectilinear motion). Point-to-point trajectory generation may be modelled as a dynamic series of point attractor systems. The human arm may be regarded as possessing two components to movement: a modifiable rest position defined in terms of Cartesian coordinates from which inverse kinematics are computed and a superimposed rhythmic position specified in joint coordinates [Schaal & Sternad 1998]. In human cognition, sensory-motor cortical maps provide the means for cyclically alternating between attentional (sensory) and orienting (motor) systems during movement to direct the agent towards its target. The cycle implements comparison between a terminal motor map and a proprioceptive motor map to determine the degree of match [Grossberg 1980]. Only when the entire map plan has been executed do the proprioceptive and motor maps match thereby terminating the movement. The humanoid robot DB is a 1.85m tall humanoid robot of 80 kg mass [Atkeson C et al 2001]. It has 30 degrees of freedom (DOF) – a 3 DOF neck, each eye with 2 DOF, two 7 DOF arms (no fingers), two 3 DOF legs and a 3 DOF trunk. Visual guided arm control is through the extended Jacobian while minimising gravitational loading. Self-organising Kohonen maps were used to store motor trajectories.

5. Onboard Power Systems

5.1. ELECTRIC POWER SYSTEMS

The electrical power subsystem (EPS) of a spacecraft provides, stores, distributes and controls the electrical power. The main function of the EPS is to provide continuous electrical power to the spacecraft subsystems throughout the mission life. In this sense, it distributes and controls the power that is fed to each subsystem in accordance with the individual demands taking into account average and peak requirements. Furthermore, it accounts for power regulation if needed and protects the vehicles against possible failures within the EPS system. The following figure summarises the functions of the power subsystem:



Different types of power sources, according each time with the specific requirements, achieve power generation within the vehicle. Photovoltaic solar cells use the solar radiation to produce electrical energy and are the most widely used power source. They convert solar radiation energy directly into electrical energy. The cells are connected in series and parallel in order to deliver a specified voltage and current. The basic organisation is modified in order to minimise the consequences of cell breakdown and the possible effect of shadow. Connecting groups of cells in parallel helps avoid loss of a whole branch of cells in case of a single failure. Key design issues for solar arrays include spacecraft configuration, required average and peak power levels, operating temperatures, shadowing, radiation environment, illumination or orientation, mission life, mass and area, cost and link. Static power sources use a heat source- typically plutonium-238 or uranium-235- for direct thermal to electric energy conversion. Dynamic power sources use a heat source and a heat exchanger to drive an engine in a thermodynamic power cycle. The heat source can be concentrated solar energy, radioisotopes, or a controlled nuclear- fission reaction.

Electrical energy produced by the solar cells as to be stored to account for the eclipse periods where there is no solar radiation and for peak power demands that may occur throughout the mission. In most cases batteries serve as energy storage units, although flywheels and fuel cells may be considered as alternatives in some cases. Batteries comprise of individual cells in series. Battery cells are divided in to primary and secondary. Primary cells are not rechargeable and are mainly used for short missions or for tasks that have low power demands. Secondary cells convert chemical energy into electrical during discharge cycle and electrical energy into chemical during charge cycle. This type of cells provides electrical energy to the spacecraft during eclipse periods and is charged in sunlight with the use of photovoltaic solar cells. Lithium batteries have high energy densities but deliver power only at low current.

The power delivered by the primary energy source, the solar cells, is dependent on the operating point. The power available though depends on the incident solar flux and the degree of degradation of the solar cells due to irradiation. It is necessary to provide conditioning circuits for the electrical energy intended for distribution to the spacecraft systems. Electrical power generation at the array should be controlled to prevent overcharging the battery and overheating the spacecraft. Power regulation divides into three main categories: controlling the solar array, regulating the bus voltage, and charging the battery. The two main subsystems of the power regulation and control system are the peak-power tracker (PPT) and a direct-energy-transfer (DET) system. A PPT is a non-dissipative dc-dc converter operating in series with with the solar array. Thus, it dynamically changes the operating point of the solar array source to the voltage side of the array and tracks the peak power point when energy demand exceeds the peak power. It allows the array voltage to go up to its maximum power point and then the converter transforms the input power to an equivalent output power of different voltage and current. Because the PPT is in series with the array it uses 4-7% of the total power. Its use is therefore advantageous for missions under 5 years where the requirement for power is greater at the Beginning Of Life than at the End Of Life. The DET is a dissipative system since it dissipates power not used by the loads. It uses a shunt regulator, operating in parallel with the array, which shunts the array current away from the subsystem when the loads do not need power.

There are three different bus control configurations: the fully regulated bus, the unregulated bus and the quasi- regulated bus. In an unregulated bus the load bus voltage is the voltage of the batteries. The regulation is dependent on the battery regulation, which significantly varies between the charge and discharge cycles. In a quasi- regulated configuration the bus voltage is only regulated during the battery charge cycle. During charge the bus voltage fixes at a potential several volts above the batteries. As the batteries reach full charge, the drop across the chargers decreases, but the bus voltage is still constantly regulated. The bus becomes unregulated during discharge when the voltage is about a diode drop lower than the batteries and decreases as the batteries further discharge. This type of configuration has low efficiency and high electromagnetic interference if used with a peak power tracker. Finally, the fully regulated power subsystem is inefficient but it will work on a spacecraft that requires low power and a highly regulated bus. It employs both charge and discharge regulators. Its advantage lies on the fact that when connected to the loads it behaves as a low impedance power supply making design integration comparatively simple.

The distribution system consists of cabling, fault protection, and switching gear to turn power on and off to the spacecraft loads. Power distribution designs for power systems depend on source characteristics, load requirements and subsystem functions. Power distribution systems can be either centralized or decentralised, depending on the location of the converters. The centralized configuration places the converters out at each load end separately, whereas the decentralised one regulates all spacecraft loads within the EPS. The decentralised approach implies an unregulated bus since distributed converters regulate power within the EPS. The centralised system though does not impose the need of a tailor- designed EPS for different applications. The following table summarises the effects of system-level parameters on the power subsystem:

Parameter	**Effects on Design**
Average electrical power requirement	Sizes the power- generation system (e.g. number of solar cells, primary battery size) and possibly the energy- storage system given the eclipse period and deph of discharge.

Peak electrical power requirement	Sizes the energy- storage system (e.g. number of batteries, capacitor bank size, etc.) and the power processing and distribution system.
Mission life	Longer mission life (>7 years) implies extra redundancy design, independent battery charging, larger capacity batteries and larger arrays.
Orbital parameters	Defines incident solar energy, eclipse/ Sun periods, and radiation environment.
Spacecraft configuration	Spinner typically implies body- mounted solar cells; 3- axis stabilised typically implies body- fixed and deployable solar cells.

5.2. BIOMIMETIC ENERGY STORAGE

We expect a plant to spend its time accumulating sugars and to generate seeds or spores only infrequently, yet the plant would be more successful if it could spend all its time reproducing, which is clearly impossible. Similarly most animals spend their time either feeding or resting and a comparatively short time is spent reproducing or travelling. The same will have to be true of autonomous robots. They will have to carry out tasks which need more energy than can be acquired from their environment during the time available to carry out the task. Currently they might do this by accumulating electrical energy in dry cells or capacitors, but the energy cannot always be delivered quickly enough from an electrical system (mechanical systems are generally much more able to deliver power), and there are significant losses involved (Tse et al., 1995). An obvious example is the Mars Rover that is required to manage its onboard energy by accumulating solar power to be used later in the mission cycle. For the foreseeable future such a class of (semi) autonomous robot will not be expected to carry out continuous action. Furthermore, the designer perhaps does not take the problem of energy into account at all, or regards it as a problem to be solved later. The processes of energy extraction and accumulation, and the mechanisms of energy management and release, are therefore vital to progress in the field of autonomous robots. There are two main classes of event - single and regenerative. Single events use a direct source of energy that is completely dissipated by the event (the jump of a flea, for example). Regenerative events are equivalent to serial events in biology, such as running where up to 50% of the mechanical energy can be taken over from one stride to the next using short-term elastic storage in the Achilles tendon and the longitudinal ligament on the underside of the foot. However an animal cannot store strain energy for more than a few seconds since it hasn't got access to suitable materials, whereas a machine using a metal spring can store strain energy for very long times. So a jumping or flying robot could be designed to have a hard landing, using the sudden deceleration to regenerate useful strain energy in its main jumping spring.

There are several uses to which the energy may be put. In nature, predator and prey may have the same physiology, so any mechanism the predator may have in amplifying its attributes will give it an advantage. A strain energy store can accelerate a predator towards its prey, as in the fast-starting pike where accelerations of over 15 g have been reported (Domenici and Blake, 1997), and the chameleon's tongue, capable of 50 g (de Groot and van Leeuwen, 2004), or simply make a device which can act faster than the prey, exemplified by the elastic mechanism of the leaf of the Venus Fly Trap (Vincent, unpublished). Another use is to overcome acceleration due to gravity, in which case the animal or robot can jump (see below), or can launch a projectile (another way of viewing the chameleon's tongue!). A third is to use the stored strain energy to generate sufficient force to be able to injure a structure or material that would otherwise be too strong, as in the snap-jaw ant (Gronenberg et al., 1998). In all these examples the main point is that the system (animal, robot) is energetically autonomous and capable of accumulating low-grade input energy to feed a power amplification system. Another aspect of jumping insects is the relationship with flight. Insects use the jump to attain a useful velocity for flight. And many of the larger insects spread their wings at the zenith of the jump and extend their range by gliding. This is a more sophisticated behaviour, but can extend the usefulness of a jump, both for range and the time for which the robot remains airborne and capable of acquiring and transmitting long-range reconnaissance data.

The most-studied mechanical power amplifiers occur in jumping insects. Even so, relatively few have been investigated, and the mechanics are generally known only vaguely, since the main interest has tended to be energetics, which requires less information on the dimensions and stresses involved. The prime examples are: locust (Bennet-Clark, 1975); flea (Bennet-Clark and Lucey, 1967); click-beetle (Evans, 1972); flea-beetle (Ker, 1977); springtails (Brackenbury and Hunt, 1993); frog-hoppers (Burrows, 2003); stick insects (Burrows and Morris, 2002). Other spring mechanisms are found in the Venus fly trap (which is most closely modelled as an anticlastic bistable - Vincent, unpublished), in the claw of the mantis shrimp (Patek et al., 2004) and in the feeding mechanism of many insects which suck liquids (Rice, 1970). The seed pods of peas and beans, and fern and moss sporangia are also powered by strain energy, but these are used once only and rely on the fracture of a brittle component to trigger the release of the strain energy. There are some common design factors.

1. Strain energy is stored only when the spring mechanism is in the position from which the energy will be released - its loaded configuration. This is in contradistinction to most man-made systems, where the assumption of the loaded configuration is also the means by which the energy is stored (e.g. drawing a bow). The insect brings its legs or its body into the jumping position, then loads the main spring using muscle power. This probably makes the system safer and allows a lower safety factor.
2. Nature commonly uses bistable mechanisms. This is intimately associated with the separation of the assumption of the loaded configuration from the storage of strain energy. The mechanism is drawn over centre by the main spring, and then the spring is loaded. Bistable mechanisms can be modelled using catastrophe theory (Thom, 1975); so far only the simplest catastrophe model has been found; would technical mechanisms be more effective were they derived from higher order catastrophes?
3. The main spring has a low mechanical advantage and can store a large amount of strain energy, generating high forces (Patek et al., 2004).
4. When the system is "fired" the trigger, which can generate only a low force but has a high mechanical advantage, allows the mechanism to move back over centre and the energy from the main spring is fed into the system. This has the advantage that there are no firing pins or hooks to jam or break. Thus control is smoother and reliability improved. An example is the Zeeman catastrophe machine (Zeeman, 1972).

The material from which the spring is made, and its geometry, have to be tuned to the mechanism which delivers the energy. Newton's laws tell us that a material which can deliver 10 J/g (locust tendon, carbon-fibre composite or bamboo) will contribute no more than 0.5% of the total weight of a robot which is required to jump to the height of 1 m, so strain energy density is probably not important. Probably more so is the strain needed to store the maximum amount of energy, which dictates much of the geometry of the system, and the time for which the energy can be stored. This militates against elastomers, which tend to relax when stressed and so lose the energy which they are supposed to be storing. The best material from the point of view of minimal hysteresis is glass or silica, but this is obviously at the mercy of small imperfections from which fractures can propagate.

We see the concept of elastic energy storage and power amplification as having two main areas of use in the design of autonomous robots. In the current technology it is likely that the lack of power on demand has led to energy problems in the design of robots being ignored or designed around. Nonetheless, the ability to jump (especially in rough terrain where wheels are less use) or to throw things vertically (e.g. a light for illumination) or over a horizontal distance (e.g. a grappling hook or anchor, a grenade) could be very useful. It may also be advantageous for wheeled vehicles to be able to call upon bursts of power when inertial energy is insufficient in overcoming an obstacle. In a truly autonomous robot, making its living from the countryside, elastic energy storage would also be useful in catching prey items (the Venus fly trap is the obvious model - more active prey items tend to have greater nutritional value), for biting or cutting strong materials or structures (e.g. the snap-jaw ant), for internal transport (e.g. intermittent pumping where a certain minimum mass has to be moved) and for jettisoning waste materials. Power amplification also allows the overall weight to be less, since an elastic energy store is much lighter than the equivalent motor, and it can be deformed by a small, low power, motor. In many natural systems, the chassis or skeleton provides the main strain energy store, so the same design approach with a robot would allow weight to be reduced further.

Bioluminescence is the production of light by organisms, eg. fireflies but is most common in a wide variety of marine animals like deep sea fishes, squid, jellyfish, crustaceans, sea squirt and worms. Bioluminescence is based on the reaction between two biological compounds, luciferin and luciferase. This may be under the fish's control or through symbiotic bioluminescent bacteria, the latter being more rare. Most importantly, bioluminescence involves the emission of light without heat. The hatchet fish Argyropelecus aculeatus has light organs along the bottom of its body facing downwards plus one light organ pointing into each eye. The fish regulates the amount of light emitted from its photophores by matching it to the ambient light, its colour and angle filtered from the surface by matching the ambient light with its output from the light organ in front of each eye. This counter-illuminates its body.

It has been suggested that the earliest organisms used pre-photosynthetic pigment-protein complexes to protect themselves from UV before the ozone layer was formed. Such proteins operate by absorbing high energy UV photons and dissipating the energy through (bacterio)chlorophyll transitions and re-emitting in the near-infrared. Photosynthesis occurs in plants algae and cyanobacteria whereby energy from sunlight powers cellular metabolism. Photosynthesis is performed in chloroplasts, plastids that evolved from free-living cyanobacteria through endosymbiosis into eukaryotic cells. Plastids maintain a semi-autonomous genome with only ~100-200 genes (compared to ~3200 genes in cyanobacteria). Chloroplasts originated from cyanobacteria once with similar reaction centre architectures but have been laterally transferred to other eukaryotic lineages. Green filamentous bacteria and purple bacteria are reckoned to be the oldest photosynthetic lineages. Red algae retain cyanobacterial phycobilisome pigments while green algae replaced then with chlorophyll b [Cavalier-Smith 2002]. Some eukaryotic groups acquired its chloroplasts from a red alga and two different green algae through secondary symbiogenesis, eg. euglena. Many photosynthetic bacteria can grow photoautotrophically, heterotrophically or adopt mixed strategies, eg. euglena. Photosynthetic activity occurs in the chloroplast membranes. Membranes are modelled as a fluid mosaic lipid bilayer in which proteins are embedded with patches of solid lipid (lipid rafts). Ion channels are the basis for selective filtering and is broadly similar in all biological cells [Lee ?]. The K+ channel is a tetramer in which each subunit contains six transmembrane alpha helices forming the membrane pore 12A long and 3A wide through which the 1.3A radius K+ ions stripped of its waters of hydration pass. Photosynthesis involves pigment-protein complexes using photon energy to drive electron transfer reactions coupled to the movement of protons across membranes. The proton electrochemical gradient is used to drive the synthesis of ATP. During photosynthesis, energy is collected by an efficient antenna system and transferred to a reaction centre complex where electron transfer occurs [Blankenship 1996]. The antenna pigment which increase the photon absorption cross section may be (bacterio)chlorophyll, caretenoid or bilin (an open chain tetrapyrrole) embedded within the membrane according to the type of organism. Most pigments within photosynthetic organisms function as antennae and have excited lifetimes ~1-5 ns which is much longer than their transfer to the reaction centre complexes ~10 ps making the energy transfer highly efficient. The structural diversity of pigments across species suggest independent evolution. The excitation energy is transferred to the reaction centre complex which results in the electronic excitation of bacteriochlorophyll within the reaction centre pigment-protein complex which resides in the chloroplast membrane. The excited molecule transfers an electron to an acceptor molecule creating an oxidised chlorophyll and reduced acceptor (redox couple). A series of electron transfer reactions occur leading to a reduced electron acceptor (photosystem II) and an oxidised electron donor (photosystem I) [Heathcote et al 2002]. In some organisms, the electron donor is water which is oxidised, liberating oxygen while the electron acceptor is carbon dioxide which is reduced to sugars. Some photosynthetic organisms contain only one photosystem (either photosystem I or II) and are characterised by anoxygenic reactions. Type II reaction centre comprises two branches, each of which consists of two molecules of (bacterio)chlorophyll, one (bacterio)phephtyin and one quinone. The type II reaction centre of plants, algae and cyanobacteria is similar in many respects to the purple bacterial reaction centre complex. The reaction centre complexes from anoygenic purple photosynthetic bacteria, eg. *Rhodobacter sphaeroides*, is well understood. They contain a core protein complex of two related membrane proteins – L (light) and M (medium). Most also contain a third protein – H (heavy) – and even a fourth protein – C (cytochrome), a four-heme containing c-type cytochrome. The D1 and D2 polypeptides of the eukaryotic and cyanobacterial photosystem II are similar in structure to L and M polypeptides of purple bacteria. Several cofactors in purple bacteria include bacteriochlorophyll a (sometimes b), metal-free bacteriopheophytins, two quinines (ubiquinone or menaquinone), non-heme Fe and usually a carotenoid. The cytochrome contains 4 heme c groups covalently bonded to cysteine residues. The reaction centre complex forms 11 transmembrane helices, 5 each from L and M and one from H. Other types of photosynthetic bacteria contain reaction centre complexes that are quite different to purple bacteria but operate on similar principles. Indeed, eukaryotic and cyanobacterial photosystem II cofactors include four chlorophyll a, two pheophytin a and two plastoquinone molecules. However unlike purple bacteria, they have in addition two light-harvesting proteins CP43 and CP47. Water oxidation in photosystem II is performed by the oxygen evolving complex of four Mn atom unique to PSII. Photosystem I of eukaryotes and cyanobacteria is larger than Type II and comprises PsaA and PsaB polypeptides with 90 light harvesting chlorophyll molecules. The electron transfer chain possesses six chlorin, two quinone and six Fe-S molecules. Phylloquinones pass electrons to the Fe-S centres. Antenna action is regulated through a mechanism by which excitation energy is dissipated by quenching before transfer to the reaction centre. This quenching during high irradiance prevents photooxidant damage within reaction centres. Xanthphylls are carotenoids which regulate this quenching forming zeaxanthin in the quenched state and violaxanthin in the unquenched stated. Enzymes interconvert these carotenoids in response to energy levels whereby violaxanthin acts as an energy donor while xeaxanthin acts as an energy quencher.

Biological systems are powered by the synthesis and storage of energy in ATP from fuel. ATP synthesase (ATPase) uses transmembrane proton gradients created by enzymes that mediate energy-generation reactions. Hydrolysis of ATPase acts as a proton pump to produce the proton gradient [Lanyi & Pohorille 2001]. ATPase acts as a dual rotor with many proton-binding sites coupled to conformation changes in ATP/ADP+P: the F_1 motor generates mechanical torque during hydrolysis of ATP while the F_1 motor generates torque ~100 pN in the opposite direction at high ATP concentrations with near 100% efficiency. F_1ATPase has been successfully bonded to Ni, Cu and Ag using electron beam lithography. Fabricated nano-propellors were attached to the ATPase which rotated at 5 rev/s. Bacteriorhodopsin functions as a light-driven proton pump with a maximum sensitivity at 570 nm across a range 500-630 nm. It comprises two components: a 248 amino acid polypeptide and a chromophore embedded within the protein. Energy is derived from photoisomerisation of the trans to the cis form of the chromophore releasing a proton. The transmembrane electrochemical gradient of protons is used to power ATPase to convert ADP+P to ATP. Bacteriorhodopsin and thermophile ATPase are unusually resistant to thermal, radiation and photo-damage. Bacteriorhodopsin is found for instance in the purple membrane of the salt marsh archaebacteria Halobacterium salionarum which lives in hot resource-limited environments. Bacteriorhodopsin immobilised on thin films of gelatine of polyvinyl alcohol can be used in 3D protein-based optical memories with high data storage capacity that can be stable for decades if shielded from blue light [Wise et al 2002]. Together bacteriorhodopsin and ATPase can form a long-lived artificial energy generation system in which a proton current is generated inward through bacteriorhodopsin and outward through ATPase powered by ATP production from ADP+P. Alternatively, a redox chain of linked carotene-porphyrin-naphthoquinone might be adopted such that carotene is oxidised, naphthoquinone is reduced with quinone transporting the electron and proton. Redox proteins and enzymes such as cytochromes execute many of the most critical biochemical reactions through electron transfer [Gilardi & Fantuzzi 2001]. According to Marcus theory, the rate at which an electron is transferred from a donor to an acceptor is given by:

$k = \left(\frac{2\pi}{\hbar}\right) V^2 FC$ where V=electronic coupling of the donor and acceptor states $= Ce^{-\beta R}$

FC=nuclear Franck-Condon factor$= \frac{1}{\sqrt{4\pi\lambda k_B T}} e^{-[(\Delta G_0+\lambda)^2 / 4\lambda k_B T}$

λ=reorganisational free energy

Activation energy, $\Delta E = \frac{(\Delta G_0+\lambda)^2}{4\lambda}$

Design of alpha-helices is preferred over beta-structures as beta-structures have more complex hydrogen bond patterns. Molecular lego is based on generating artificial redox chains by assembling genes of well-characterised redox proteins and enzymes. Conducting polymers such as poly(aniline) or poly(3-methyl-thiphene) alter their conductivity by many orders of magnitude on oxidation and reduction. They can be used to fabricate microelectrochemical transistors. Fish such as Electrophorus electricus possess electrical generator organs which resemble a fuel cell system. Their cytoplasmic membranes allow K+ or Cl- ions to pass more easily than Na+ ions so that the K+ ion concentration within the cell is 20-30 times higher than outside the cell generating an EMF of ~77 mV. Biocatalytic fuel cells can produce practical levels of electric power using immobilised microorganisms or enzymes as catalysts and glucose as a fuel [Sasaki & Karube 1999].

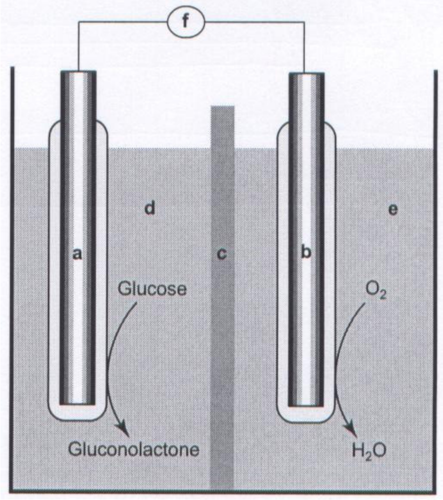


Fig 5-1 Biocatalytic fuel cell containing anode coated with immbilised glucose oxidase (a), cathode coated with immobilised glucose oxidase (b), ion-exchange membrane (c), glucose solution electrolytes saturated with oxygen (e) with electrodes connected by electric circuit (f): Glucose + O_2 $\rightarrow$ Gluconolactone + $H_2OH_2O_2$ [from Sasaki & Karube 1999]

Enzymes such as glucose oxidase immobilised onto an electrode surface may act as a micro-battery. Hydrogen-producing bacteria consume organic compounds to produce hydrogen which may be used as a fuel. Mitochondria in eukaryotes oxidise organic compounds - glucose is oxidised by oxygen (which is reduced to water) through glycolysis and the citric acid cycle reducing nicotinamide adenine dinucleotide (NAD) or nicotinamide adenine dinucleotide phosphate (NADP) to NADH or NADPH. There are three kinds of fuel cell. A biochemical fuel cell has an anode inserted in a bacterial suspension that produces hydrogen when fed with glucose which is oxidised at the anode. Oxygen is reduced at the cathode generating an electric circuit. Such a cell has been produced by immobilising hydrogen-producing bacteria Clostridium butyricum in a polyacrimide gel, the hydrogen being transported to a phosphoric acid fuel cell. It produced a power output of 13W. A photochemical fuel cell using photosynthetic bacteria such as Rhodospirillum rubrum or cynanobacteria such as Anabaena N-7363 converts hydrogen into electric current with an efficiency of >80%. An enzyme battery uses biocatalysts such as methanol dehydrogenase or glucose oxidase with mediators such as phenazinium methosulphate or tetrazolium. The fuel – methanol, formate or glucose – is reduced and electrons transferred to the anode by the mediators. Such fuel cells may be constructed from micromachining techniques such as anodic bonding and anisotropic etching. Such fuel cells would be particularly useful for microrobots which must carry their own power.

The University of West of England has developed a robot – EcoBot II - that digests flies in a series of microbial reactor fuel cells to generate electricity. The energy source is sugar in the polysaccharide in the chitin of the fly's exoskeleton. Bacteria in the fuel cell breaks down the sugars releasing electrons which reduce sulphates to sulphides. At the anode, sulphides react with water and oxidized to sulphates releasing electrons at the anode generating electric current. EcoBot has a maximum speed of 10 cm/h and every 12 minutes moves 2 cm. This concept probably has little use for space systems unless energy generation mechanisms of chemolithoautrotrophs may be exploited.

5.3. THERMAL CONTROL SYSTEMS

In this section, we consider thermal control as a power dissipation function. The various components of satellites have better performance when they remain in the same constant temperature within certain limits. Each component has a different range of allowable temperature limits. For that specific reason thermal control on a spacecraft is essential. The temperature of an object is changed by the effect of heat transfer. Heat transfer is effected via conduction, convection, or by radiation. All these processes are effective in the space environment within our spacecraft. The thermal control payload is usually mounted in the interior of the satellite. This avoids direct contact with the outside environment. Heat generated from the various electronics and subsystems needs to be carried away to prevent any unwanted temperature rise, which will eventually effect the reliability of the spacecraft.

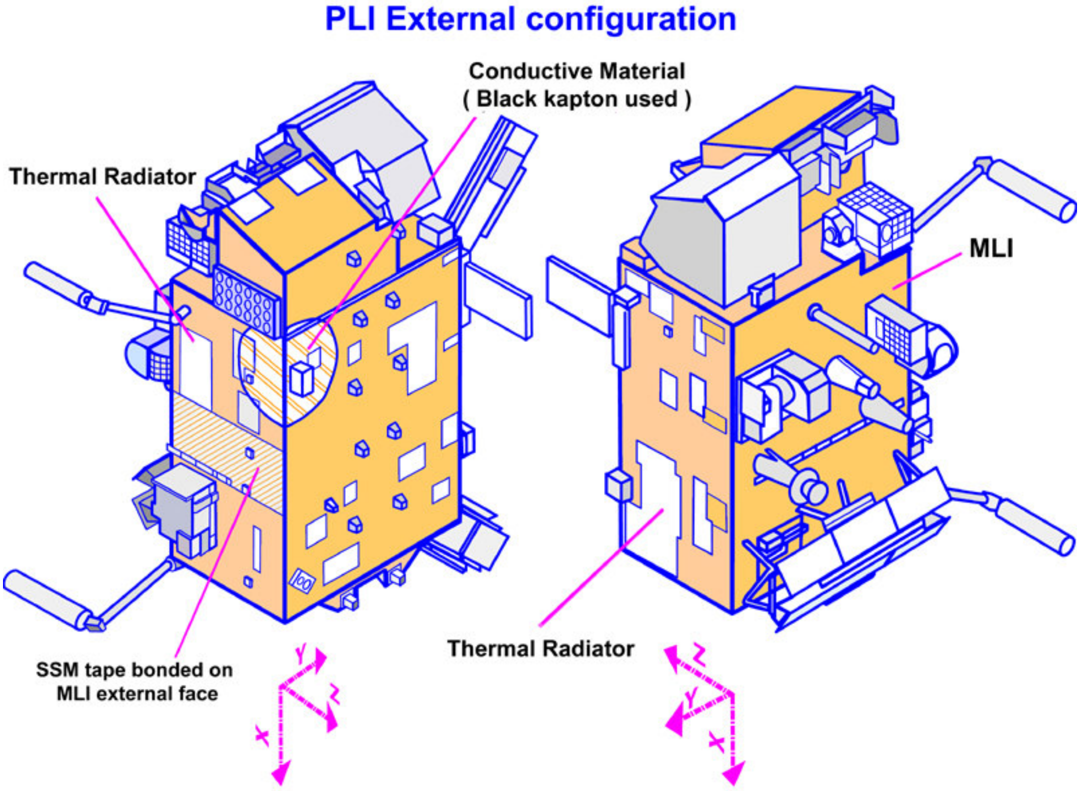


Fig 5-2 Thermal Control Payload example (source ESA)

The spacecraft thermal environment is designed as such to reflect radiation from the Earth emissions, reflect Earth reflection (Albedo Radiation), to provide insulation from the direct solar radiation and provide aerodynamics heating protection as well. For the thermal design we take into consideration the emissivity, the absorptivity, the reflectivity and the transmissivity of the each subsystem, on our spacecraft. Each subsystem dependant of its material, on the color of the material, and its transparency, has different values of the above properties. For that reason in order to control the temperature properties of the subsystems, they are painted accordingly. As an example when a device is painted blacks has very high absorptivity but when it is painted white has very low.

The absorptivity is calculated from: $a_\lambda = q_\lambda{}^a(T)/q_\lambda{}^i(T)$

Where a_λ is the spectral hemispherical absorptivity, $q_\lambda{}^i(T)$ is the spectral radiation flux incident upon a surface, and $q_\lambda{}^a(T)$ is the amount of radiation absorbed. The thermal model equation for a satellite is calculated from:

$$q_s + q_r + q_E + q_I = \sigma A_u \int_0^\infty \varepsilon_\lambda T_u^4 d\lambda + (MC)_u \frac{dT_u}{dt}$$

where q_s is the absorbed isolation

q_r is the absorbed earth albedo radiation

q_E is the absorbed earth emission

q_I is the radiation emitted within the vehicle

$\sigma A_u \int_0^\infty \varepsilon_\lambda T_u^4 d\lambda$ is the radiation emitted from vehicle to deep space

$(MC)_u$ is the thermal capacity of the vehicle

T_u is the vehicle mean temperature

The temperature distribution within an earth satellite is first calculated by measuring the thermal inputs to the various satellite surfaces from the earth and the sun for a particular orbit. Radiation interchanges between the surfaces of a satellite should be accounted as well. The second stage is to calculate the internal heat inputs and heat dissipation within the satellite and take into account the thermal capacities and the thermal resistances between the parts of the satellite. For mathematical calculations the spacecraft model is split into a number of nodes. In each node lumped component techniques are applied.

Thermal control is achieved with the use of heaters and thermostats. During extreme cold case conditions the minimum allowable temperature needs to be sustained. Thermostatically controlled thin-film heaters are bonded to the equipment. The heaters are strips of kapton with etched foil heating elements and welded power leads. A number of materials have been developed to provide thermal control. The ones mostly used are Teflon, Kapton and Mylar which with combination with other metal deposits and paint produce the desired thermal control effects. An example of a combination of these materials is the MLI (Multi-Layer Insulation Blankets), which compromise of multilayer of Teflon and Kapton, interspersed with Dacron netting and are used to provide protection from the rays of the sun. These materials though degrade over time with main causes of degradation being, handling, the solar ultraviolet radiation, the particulate radiation, the out gassing in a hard vacuum, the extreme temperatures and the micrometeoroid erosion.

The thermal control devices provide either active or passive control. For active control, louvers are used which dampen the temperature variations caused by fluctuations in internal heat dissipation and orbital fluxes. Louvers consist of highly polished aluminium blades suspended on their ends along their length onto a frame, driven by bimetallic temperature sensors. Dependant on the internal temperature they open and close when the temperature is high and low respectively. For passive control appropriate exterior phases are chosen or tapes that have the appropriate absorptivity and emissivity.

5.4. BIOMIMETIC THERMAL CONTROL

Biomimetic methods of thermal control are appropriate to spacecraft and would be entirely compatible with incorporation of thernal control pathways within multi-functional structures. Reptiles are ectothermic while mammals and birds are endothermic. Reptiles – lizards, snakes, crocodiles and turtles - alternate between the sun when they are too cool and the shade when they are too warm to maintain their body temperatures at optimum levels of about 35^{o}C or so. Spacecraft endure similar thermal cycles but dictated by celestial mechanics rather than for thermal control. Reptiles rely on anaerobic processes so adopt and waiting strategy for capturing prey, expending energy rapidly but at the price of long recovery periods. Endotherms however internally maintain their body temperatures at 37^{o}C at all times through homeostatic metabolic activity to provide high stamina for chasing prey and rapid recovery. Unlike reptiles, amphibians do not possess waterproof skins so they live in damp places or in water, and most of them are cold as they avoid sunlight which would dehydrate them through evaporation. Reptiles generally consume about two to three times their body weight per year while mammals generally consume around 20 times their body weight to maintain an active metabolism. Indeed, predatory birds (raptors) consume around 55 times their body weight annually – their home ranges are very large. As in spacecraft systems, active thermal control is more costly in energy than passive thermal control. The most active reptilian predator is the Komodo dragon.

We do not consider biomimetic thermal control further in this report.

6. Onboard Data Handling Systems

6.1. INTRODUCTION

The command of a satellite is separated in two parts: the on board systems and the ground control segment. The ground segment tracks the satellite motion with the antenna system. Processes, records and analyses the telemetry data received from the satellite and transmits commands to the satellite using high power uplink signal. There are a number of different telecommand systems. A simple system sends the command in real-time, which are then decoded by hardware logic. Only the authorized commands are implemented. In order for a command to be implemented a security access authorization procedure takes place. The command validation is provided to ensure inadvertent commands cannot take place, only authorized users can make commands and the dangerous commands are not easily operated. On the spacecraft, a diary system is operating which use real-time on-board clock to implement a series of stored commands.

An enhanced command system is on board data handling (OBDH). The commands are received from the ground station and take the form of uplink program data. The commands are passed via the command system to the various subsystems of the spacecraft such as the on board computer and the payload. As the computer on board the satellite is constantly monitoring the condition of the spacecraft it can generate commands and the on board data handling system issue's the commands for house keeping operations, as a result of measured telemetry. This is a form of an autonomous system.

More intelligent systems use commands which are issued in order to overcome a situation which was not foreseen by the original mission parameters. This provides a mission security in the event of loss of connection with the ground station. In this event the on board computer, continuous to function, monitoring telemetry data and generating commands. When a command is issued from a ground station is first received from the command receiver on-board the satellite then demodulated, decoded from the command decoder, verified from the OBDH interface, multiplexed and latched in the forms of lines and transmitted to the various systems. There are two types of command issued for a satellite platform; command used to control the spacecraft sub-systems and command used to control extremely sensitive systems which might set in danger the entire mission. Commands used for the sub-systems are for redundancy switching, power system configuration and switching, power distribution control, ADCS operation, thermal system, OBDH configuration, payload configuration and operation and for the telemetry and command system. Special command for the propulsion system, the deployment system, the solar panel tracking and the pyrotechnic devices need special authorization and are treated as extra sensitive.

For data handling the onboard computer is responsible for overall management of a spacecraft's activity. The on board computer (OBC) has a microprocessor which is powerful, re-programmable, small and low-power, provides control and processes telemetry data. Typically it is used for telemetry formatting, command scheduling, attitude orbit and control, data collection from the various sensors, experimental control, communications processing and image processing.

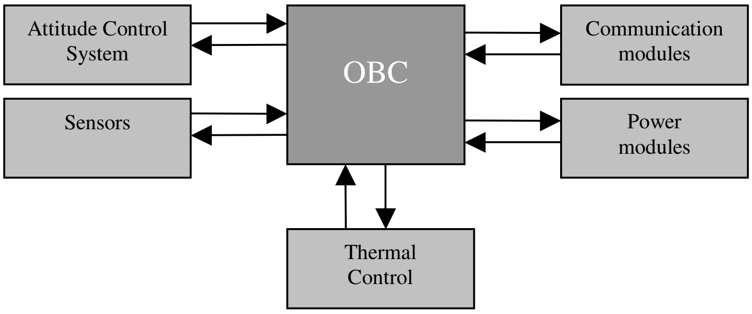


Fig 6-1 On Board Computer Connections Diagram

The OBC maintains timing, interprets commands from the Earth, collects, processes and formats the telemetry data which is to be returned to Earth, and manages high-level fault protection. The OBC has a spacecraft clock which is a counter maintained by the command and data subsystem. It meters the passing of time during the life of the spacecraft, and regulates nearly all activity within the spacecraft systems. Many types of commands up-linked to the spacecraft from the earth station are set to begin execution at specific spacecraft clock counts. The OBC performs receiving and gathering of telemetry data. The telemetry of the spacecraft is typically a mixture of science data from the experiments and spacecraft engineering or health data. Engineering or health data is composed of a wide range of measurements, from switch positions and subsystem states to voltages, temperatures and pressures. Telemetry may be transmitted in real time, or it may be written to a data storage device until transmission is feasible as it happens in the case of low earth orbit satellite which views the earth station for a small amount of time per orbit.

The OBC uses to store the data a tape recorder. It is a mechanical device for recording digital information on magnetic tape and for playing back the recorded material. The amounts of data that can be stored are very large and they can play back for downlink when requested. For smaller amounts of data random access memory, which the solid-state equivalent of a tape recorder can be used. Banks of RAM can store large quantities of digital information without any moving parts but are a lot more susceptible to failures. For fault protection the OBC uses special algorithms, which normally reside in more than one of a spacecraft's subsystems, which insure the ability of the spacecraft to both prevent a mishap and to re-establish contact with ground station if a mishap occurs and contact is interrupted.

Standard buses typically include three power lines – ground reference (GND), main system power voltage (VDD), and switched 5 V reference supply (VREF). Serial bus typically comprises 4 signal lines. Controller area networks (CAN) is a shared broadcast bus with speeds up to 1 Mbp based on variable length frames of 0-8 bytes. Four serial communications channels on the bus are a chip-enable signal (CE), a data strobe (STR), serial data line (CIN) and a clock signal (CLK). The CE and STR signals tell the sensors when they should be reading or ignoring incoming data. At the beginning of a communication from the controller, CE bit goes high and a 4-bit chip address is put on the serial data line (CIN). Each sensor has a predefined address and will only listen to a message with a matching address. At the end of the address, the STR line goes high to mark the beginning of a sensor-specific message. This message begins with a 3-bit command code followed by a 5-bit element address. The 5-bit element may access up to 32 sensors and 32 actuators or registers. At the end of the message, STR goes low. CLK line is available for read-our circuitry. Once data has been read by the controller, CE line goes inactive to reset the bus interface and disable the output.

Rent's rule determines the number of pins for a given module is a power law dependent on the number of gates in the module: $P=KG^p$ where P=no. pins, G=no. gates, K=no. pins per gate ~7, p=exponent=0.21 for VLSI systems.

6.2. COMPUTATIONAL ARCHITECTURES

Distance is the defining factor for spacecraft autonomy which introduces a communication latency. This effectively limits mission duration on the basis of mean-time-to-failure (MTTF, (1/e)~36% of components failed). The need is for software that can learn and adapt on its own to provide self-healing capable of 10^{15} operation/second/kg [LaForge 2000]. It is ultimately desirable to yield MTTF up to 100 years. The highest cost lies in the layout for the processor architecture (eg. n-node binary hypercube architecture yields $O(n^2)$ area and O(n) length and $O(n^4)$ time delay costs) but 3D free-space optical interconnects offers a means to alleviate this. N processing nodes can be connected by point-to-poimnt edges where each edge carries signals over one or more parallel channels. The K-cube (hyper-cube) architecture lies at the basis of the STAArchitecture and represents the most efficient architecture.

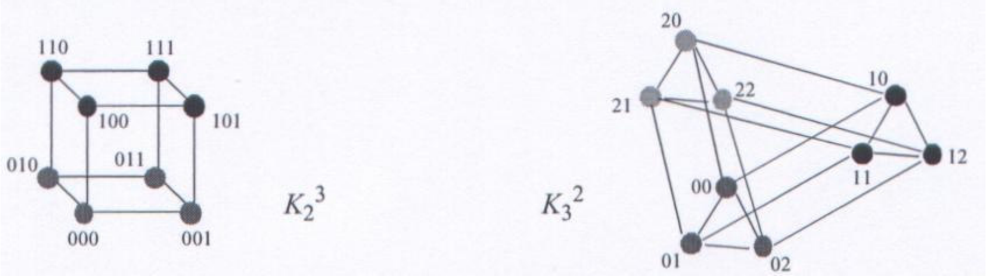


Fig 6-2 Gray code labelling of 3D K_2 cube and 2D K_3 cube [from LaForge 2000]

The K-cube connected edge represents a minimum cost architecture with maimum fault tolerance and optima performability. The approach is based on computational nodes connected by 3D technology which is hardened to 10^4 Mrad (Si) with shielding providing 1 rad(Si)/s beyond the Earth's radiation belts (cumulated over the mission lifetime) not accunting for linear energy transfer events such as SEU. Multichip modules (MCM) introduce the use of wafer stacks. Self-configuring uniform computational nodes which maintain connectivity among healthy nodes and disconnect out faulty nodes is the approach most desired. Self-healing optical interconnect ProtoStar multicomputer architecture based on the STAArchitecture.

6.3. BIO-INSPIRED SOFTWARE PROGRAMMING

Genetic programming offers promise for space application as it provides a form of automatic programming yielding programs which are analysable – this theoretical analysability is little different from that applicable to human programmer generated code. In both cases, as code becomes more complex, proof of correctness is academic and the only way to test such code is through testing through cases under nominal inputs and extreme inputs. Nevertheless, genetic programming offers a route through which biomimetic techniques will have little perceived hindrance to adoption in space software. Genetic programming is a version of genetic algorithms which exploits symbolic processing of computer programs. The objects of the population are computer programs, eg. LISP [Koza 1993] – LISP is particularly suited to genetic programming due to its syntax of lists using constant or variable atoms without distinguishing between program and data. Both list and atoms are referred to a symbolic expressions (S-expressions). Any S-expression can be represented graphically as a hierarchical rooted point-labelled parse tree with ordered branches. The external leaves of the tree are labelled as terminals. The internal nodes are functions and the root is the main function. Genetic programs involves automatically discovers a computer program that generates some desired output in response to particular inputs by searching the space of possible computer programs. Initially, a population of computer programs is created at random and genetic operators are applied to the population iteratively. There are five parameters that require definition for genetic programming:

(i) set of terminals (inputs) T, eg. T={A0, A1,..D0, D1,…,…}
(ii) set of functions (mathematical and conditional logic operations) F, eg. F={AND, OR, NOT, IF} which can compute any Boolean function
(iii) fitness measure defining performance such as multi-objective function or solution error
(iv) run control parameter
(v) termination criteria

Breeding is performed using Darwinian selection with differential reproduction of the fittest programs using the genetic cross-over operation. Only the fittest computer programs are replicated into the next generation (asexual reproduction). Fitness is measured as the sum or average over a number of representative different situations (fitness cases). Cross-over is used to create new offspring programs from two parental programs based on fitness. By randomly recombining parts of different programs, new programs may be even fitter in solving the problem. Crossover resembles sexual reproduction by operating on two parental programs selected with a probability based on fitness to generate offspring comprised of random parts of the parental programs. The cross-over operation creates these new offspring by exchanging sub-trees between the two parents, the cross-over point being selected randomly. Because entire sub-trees are swapped, the cross-over operation always produces syntactically and semantically valid programs as offspring. For example, consider two parental LISP S-expressions:

(OR **(NOT D1)** (AND D0 D1))
(OR **(OR D1(NOT D0)) (AND (NOT D0) (NOT D1)**)

If the cross-over point is defined as NOT in the first parent and AND in the second parent, cross-over yields one of the offspring of the form:

(OR (AND (NOT D0) (NOT D1)) (AND D0 D1))

This is the exclusive OR function. Mutation may also be used in genetic programming but is used rarely. After the genetic operations have been performed, the new generation replaces the old one. The process is repeated iteratively generating higher average fitness populations of computer programs – most individual computer programs generated will be useless, but a small number will have improved fitness which will tend to proliferate. The search space is the hyperspace of all LISP S-expressions composed of the atoms particular to the problem domain. The steps in genetic programming are given by:

1. Generate initial population of random compositions of functions and terminals
2. Iteratively perform the following steps:
    (a) execute each program in population and assign a fitness value from the fitness function (this is the most computationally intensive procedure)
    (b) create new population by applying two genetic operations with probability based on fitness:

    (i) reproduce existing programs into new population (asexual reproduction)
    (ii) create offspring programs from two existing programs by recombining randomly chosen parts through cross-over at a random cross-over point (sexual reproduction)

3. Best-so-far individual program is selected as approximate solution.

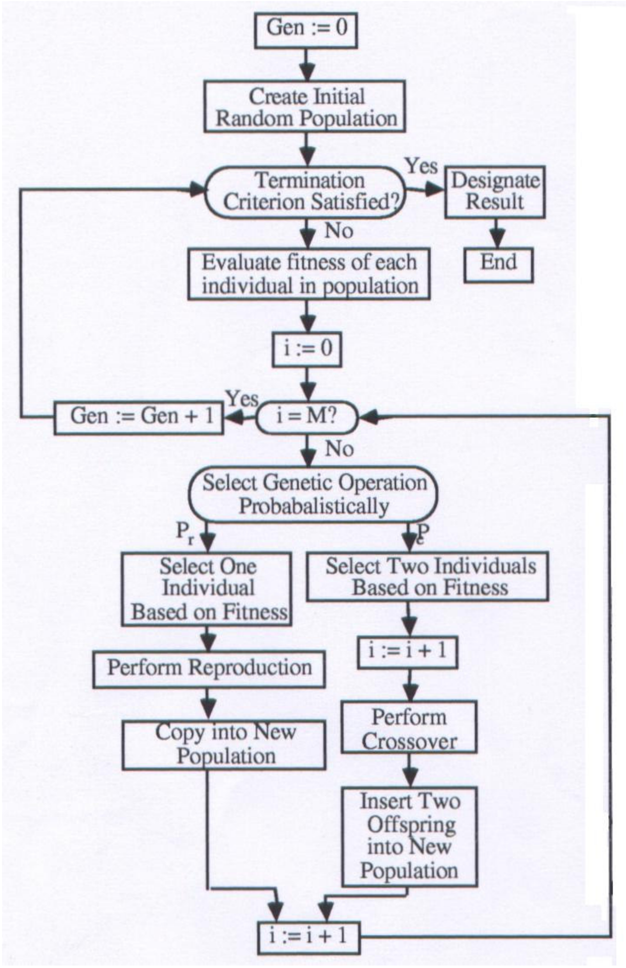


Fig 6-3 Flowchart for genetic programming

The fitness function may be expressed as the sum of squares of distances between the program output value in the solution space and the correct value:

$0 < F(i,t) = \frac{1}{(1+f(i,t))} < 1$

Raw fitness, $f(i,t) = \sum_{j=1}^{N} |S(i,j) - C(j)|^2$ where N=number of environmental cases

S(i,j)=output from program for environment j
C(j)=correct output for environment j
t=generational time step
i=individual program

The closer f(i,t) to zero the greater the fitness. Each fitness value is normalised across the population of M programs:

$$F_n(i,t) = \frac{F(i,t)}{\sum_{k=1}^{m} F(k,t)}$$

This defines the probability of copying program i into the next generation. Automatically defined functions (ADF) are functional reusable subroutines that allow scaling to more difficult problems [Koza 1992, 1993, 1996]. The body of the ADF contains a dummy variable within the function but is not declared as a global variable. In addition, the function defines the value to be returned by the function. For example, (defun function_x (arg0, arg1,…)) in LISP allows assignation of a function name with arguments allowing it to be referenced, eg. odd-2-parity XOR function may be defined as:

```
(defun xor (arg0, arg1)
  (values (or (and arg0 (not arg1))
                  (and (not arg 0) arg1))))
```

The even-4-parity problem may be thus written:

```
(xor (xor d0 d1) (not (xor d2 d3)))
```

Each computer program in the population contains one or more function defining branches and one or more main result-producing branch. The result-producing branch can call one or more defined functions, and function-defining branches can refer to other function-defining branches thereby generating a hierarchical program structure. When cross-over is performed, one of 8 types is assigned to each potential cross-over point to enable conservation of structure:

(i) root
(ii) top point
(iii) name
(iv) argument list
(v) function in function-defining branch
(vi) function in results-producing branch
(vii) body of automatically defined function
(viii) body of results-producing branch

Cross-over will only exchange a subtree from a function-defining branch with a sub-tree from another function-defining branch or cross-over will exchange a subtree from a result-producing branch with a sub-tree branch from another result-producing branch. In this case, it is necessary to determine the architecture of yet-to-be-evolved programs by defining:

(i) number of function-defining branches
(ii) number of arguments in each function-defining branch
(iii) nature of hierarchical referencing allowed between function-defining branches

However, this may not be possible so it is preferable to evolve the architecture. Changes in the architecture of multi-part programs during a genetic programming run corresponds to a change in the biological genomic structure such as increased genome lengths. Gene duplication is one such process which subsequently may evolve to be recruited to different functions, eg. trypsin and chymotrypsin, microtubules and actin, myoglobon and haemoglobin, light and heavy immunoglobin chains, etc. In addition to traditional genetic programming steps, additional architecture-altering steps are added after the genetic operators. Branch Duplication duplicates one program branch (on basis of fitness); Branch Deletion deletes a branch to counteract program growth (selected randomly); Argument Duplication adds an argument to the selected function (selected randomly); and Argument Deletion deletes arguments from a selected function (selected randomly) – these functions allow the use of uniform architecture initial populations without automatically defined user functions [Koza 1990, 1995]. The use of hierarchical automatic definition functions speeds up genetic programming evolution by a factor of 2-4 and yields structural complexity of solutions by around 20%. Parsimony pressure of the form $F(i) = P(i) - p(s_i)$ has been adopted as a means to counter program growth in genetic programs characteristic of variable length coding evolution but this degrades the performance where P(i)=performance of individual i, s_i=size of i, p=amount of parsimony pressure=αs_i. [Soule & Foster 1998]. Such code growth primarily due to cross-over introduces introns which are inoperative coding sections. Price's Covariance and Selection Theorem relates the change in frequency of a gene in a population from one generation to the next to the covariance of the gene's frequency in the original population with the number of offspring produced by individuals in that population [Langdon 1995, 1997]. Holland's schema theorem can be derived from Price's theorem [Poli & Langdon 1998]:

$$E\{m(H,t+1)] \geq m(H,t)\tfrac{f(H,t)}{f(t)}(1-p_m)^{O(H)}\left(1-p_c\tfrac{L(H)}{N-1}\left(1-\tfrac{m(H,t)f(H,t)}{M\bar{f}(t)}\right)\right)$$

where m(H,t)=number of strings matching schema H at generation t
f(H,t)=mean fitness of strings matching H
$\bar{f}(t)$=mean fitness of strings in population
p_m=probability of mutation per bit
p_c=probability of crossover
N=number of bits in strings
M=number of strings in population
E[m(H,t+1)]=expected number of strings matching schema H at generation t+1
O(H)=number of non-# symbols of schema H
L(H)=distance between furthest two non-# symbols of schema H

Fisher's fundamental theorem of natural selection states that the rate of increase in fitness of any organism at any time is equal to its genetic variance in fitness at that time. The rate of increase in the mean fitness of a population is equal to the population's additive variance for fitness. Natural selection thus generates a continual increase in mean fitness in a population. The ability of a population to increase in fitness is proportional to the variance in fitness of the population. This stresses the importance of the fitness function in genetic programs to guide the evolution of the population – this favours a dynamic fitness function which alters as the population evolves to emulate the red queen effect. This favours the use of co-evolution. Evolution offers the possibility of increasing evolvability of genetic programs through the production of increasingly fit offspring due to the building block hypothesis and duplication of blocks of code [Altenburg 1994]. It is this duplication of fit segments of code that leads to greater evolvability.

Genetic programs have been applied to a number of different applications:

- Learning of functions (eg. multiplexers)
- Robot planning
- Automatic programming
- Sequence induction
- Pattern recognition
- Optimal control
- Symbolic data regression
- Empirical discovery
- Minimax strategies
- Neural network training

A typical genetic program uses a population size of 500 programs with cross-over performed on 90% of the population the other 10% being reproduced asexually. Depth of programs must be restricted, eg. initial programs to 6 and cross-over operations to 17. The number of runs that must be processed:

$R(z) = \left\lfloor \frac{\log(1-z)}{\log(1-P(M,i))} \right\rfloor$ where z=probability of yielding solution by generation i
M=population size
P(M,I)=cumulative probability of success (experimental)

Generally, most evolution occurs within the first 20-30 generations due to early convergence so genetic programs are rarely run beyond generation 50.

For example, the nonlinear econometric exchange equation may be defined as [Koza 1991]:

Price, $P = \frac{MV}{Q}$ where M=money supply
V=money flow
Q=gross national product

The problem is to evolve this symbolic equation from actual observed noisy time series data. A truck-reversing problem where the control variable u(t) is defined in terms of T={x, y position, $\tan^{-1}(x/y)$, $\Delta\theta_{o/p}$}. Function set F{+,-,*,/, ATAN, IF.LT.ZERO} and fitness was an error measure in a number of simulated cases.

The artificial ant problem attempts to find the Santa Fe trail of food in 89 cells in a 32x32 grid. The trail is irregular and has gaps. The artificial ant begins at (0,0) and faces east and has a sensor that can see only a single neighbouring cell in the direction the ant is facing. The ant may move forward, turn right, turn left or sense the contents in the next forward cell at each time step. In this case, F={IF-SENSOR, PROGN}, T={ADAVANCE, TURN_RIGHT, TURN_LEFT} where PROGN that executes it arguments in sequence [Koza 1990]. Within 7 generations, a parsimonious solution was evolved picking up 89 out of 89 food pellets:

```
(IF-SENSOR (ADVANCE)
   (PROGN (TURN_RIGHT)
               (IF-SENSOR (ADVANCE) (TURN-LEFT))
               (PROGN (TURN-LEFT)
                          (IF-SENSOR (ADVANCE)
                               (TURN-RIGHT))
                          (ADVANCE))))
```

Conway's game of life and Lindemeyer's L-systems suggest how repetitive application of simple rules can generate complex emergent behaviours. The goal in this case was to evolve individual ant behaviour that collective ant behaviour is generated whereby food is transported to the nest through the deposition of pheromones [Koza 1990a,b, 1992, 1994]. Each of 20 ant starts initially at the nest in random facing directions on a 32x32 grid with 144 pellets of food piled 8 deep in two 3x3 piles. In this case, T={MOVE_RANDOM, MOVE_TO_NEST, PICK_UP, DROP_PHERMONE, IF_FOOD_HERE, IF_CARRYING FOOD, MOVE_TO_ADJACENT FOOD_ELSE, MOVE_TO_ADJACENT_PHEROMONE_ELSE, PROGN}. Fitness was evaluated on how many of the food pellets were transported to the nest within an allotted time of 400 time steps. A simplified version of the program generated at generation 38 was:

```
(PROG (PICK_UP)
         (IF_CARRYING_FOOD
          (PROGN (MOVE_TO_ADJACENT_PHEROMONE_ELSE
                      (MOVE_TO_ADJACENT_FOO_ELSE (PICK_UP)))
                     (MOVE_TO_ADJACENT_FOOD_ELSE (PICK_UP__
                     (MOVE_TO_NEST) (DROP_PHEROMONE)
                      (MOVE_TO_NEST) (DROP_PHEROMONE))
           (MOVE_TO_ADJACENT_FOOD_ELSE
```

```
                    (IF_FOOD_HERE
                         (PICK_UP)
                     (MOVE_TO_ADJACENT_PHEROMONE_ELSE (MOVE_RANDOM))))))
```

It is possible to co-evolve two or more populations of computer programs simultaneously [Koza 1990]. Each population acts as the environment for the other. Each individual in the first population is evaluated for relative fitness by testing it against each individual in the second population and simultaneously vice versa. By using such changing environments, this prevents loss of diversity and over-fitting of solutions. Over a period of generations, individuals with high absolute fitness may evolve as the two populations bootstrap each other to higher levels of fitness. Differential pursuer-pursuit games are two-person zero-sum games in which predator P attempts to capture a slower moving evading prey E. They are implemented within discrete, grid-like world of cells and so represent "toy" worlds. The player chooses a direction in which to move at a constant speed. The value of the game is payoff (time). The pursuer's control variable beginning at (0,0) was ϕ moving at speed w_p while that of the prey was ψ at position (x,y) moving at speed w_e where $w_p < w_e$.

The optimal pursuer strategy emerged after 17 generations:

```
(/ (- (/ (+ (* 2.0 Y) –0.066) –0.365)
     (/ Y –0.124))
   (+ EXP X ) Y –0.579))
```

ie. $\frac{\frac{2y-0.066}{-0.365}+\frac{y}{0.124}}{e^x+y-0.579}=\frac{2.58y+1.81}{e^x+y-0.79}$

This corresponded closely to the arctangent function.

Genetic programming has been applied to mobile robot tasks such as moving a box from the middle of an irregularly shaped room to the wall [Koza & Rice 1992]. The sensors provide the inputs to the genetic program while actions are the output. The mobile robot motor actions are defined by move forward, turn right and turn left. It possesses a bump sensor, a stuck sensor and 12 sonar sensors each covering 30°. A mobile robot control problem of moving a box in the middle of an irregularly shaped room to the edge was evolved with T={SENSORA_1, SENSORA_2, …., SENSORB_1, …, SENSORM_N, MOVE_FORWARD, TURN_RIGHT_30°, TURN_LEFT__30°} and F={IF_BUMP, IF_STUCK, IF.LE, PROGN2}. IF.LE allows conditional behaviours based on sensory measurements of the environment. Fitness was defined as the sum of distances between wall and nearest point on the box to the wall. The initial population size was 500 and a maximum run of 51 generations defined the termination condition. A successful program was evolved in generation 45. Similarly, genetic programming was applied to mobile robot navigation in generating a subsumption-type architecture of interacting task-achieving behaviours with hierarchical suppression to implement wall-following [Koza 1992]. Essentially, the subsumption architecture implements an if-then conditional program of the form:

```
(IF AP1 BEHAVIOUR-1
     (IF AP2 BEHAVIOUR-2
          (IF AP3 BEHAVIOUR-3)))
```

Such behaviours may include STROLL, AVOID, ALIGN and CORRECT – collision avoiding wandering is enabled by STROLL and AVOID behaviours. Wall-following is enabled with the addition of ALIGN and CORRECT behaviours. An additional motor behaviour of move backwards by a fixed amount was added to the robot actions. The genetic program was evolved using the following LISP functions: IF.LT, AND, OR, NOT, COND. Terminal set T included additionally EDGE (edging distance between robot and wall) and MSD (minimum safe distance between robot and wall). Fitness was defined as distance travelled along the wall. The population size was 1000 with a maximum run of 101 generations. Cross-over was applied to 90% of the population and the other 10% were replicated (no mutation). A simplified version of the evolved program was given by:

```
(PROGN
    (MB)
    (IFLTE (IFLTE S08 MSD MSD S05)
             S09
        (MB)
        (PROGN (IFLTE (IFLTE S08 MSD MSD S05)
                              (PROG1 S10 (MF) (TR))
                    #
                    (TR))
                    (MB)))
(MB)
(IFLTE (PROGN (IFLTE S00 S07 # (MB))
                   (IFLTE S00 S07 # (MB))
                    (TL)
                   S09)
        S05
(PROGN (MF) (TR) (MB))
(PROGN (TL) (MB) (TL)
           (IFLTE S00 (IFLTE S08 MSD MSD S05) (MB) #))))
```

Genetic programming was also used to evolve primitive behaviours and an arbitration coordination system to generate both box-pushing and box-side following on a khepera robot [Lee et al 1996, Lee 1999]. This emulated a general process of attempting the evolve controllers for more complex tasks whereby tasks are decomposed into behaviour-based architectures and then evolving separate behaviour modules and coordinating arbitrators [Lee 1999]. This essentially involves shaping the problem into simpler subgoals so reducing the search space. Lower level behaviours are evolved first and separately and control systems evolved on top of the lower levels – this is similar to behaviour-based approach but does not involve hardwiring. The box pushing fitness function favoured keeping activation of the front IR sensor high while moving the robot forward:

$$F(C)=\sum_{t=1}^{T}\alpha(1-s(t))+\beta(1-v(t))+\gamma w(t)$$

where s(t)=average of normalised front sensor activations
v(t)=normalised forward speed
w(t)=normalised speed difference of two wheel motors

Two populations of 50 programs were evolved over 50 generations yielding a solution of the form:

```
(PROG
(OR (>=0.13 IR0)(>=0.13 IR0))
(<=IR1 IR1)
(XOR (>=IR3 IR7)(OR(>=0.13 IR0)(>=0.13 IR0)))
(>=IR1 0.36)
(>=IR1 IR1)
(XOR (>=0.13 IR0)(>=IR2 0.13)))
```

The box-side circling fitness function keeps the robot moving forward and circling along the sides of the box:

$$F(C)=\sum_{t=1}^{T}\alpha.abs(s(t)-k)+\beta(1-v(t))$$

where k=predefined constant quantifying the distance between a robot and box

Two populations of 50 programs were evolved over 50 generations yielding a solution of the form:

```
(PROG
(NOT (>=IR6 IR1))
(>=IR1 0.78)
(OR (>=IR5 IR1)(>=IR3 IR3))
(OR (>=0.32 IR3)(>=IR5 IR4))
(>=IR4 IR3)
(OR (>=IR5 IR1)(>=IR6 IR3)))
```

An exploration behaviour was evolved to minimise the number of unexplored regions with a fitness function of the form:

$$F(C) = \alpha(1-P) + \beta(1-M)$$

where P=proportion of space visited (quantified as a grid of cells)
M=average speed of robot

A third controller acting as a decision-maker was evolved to keep the robot close to the centre of the room with a fitness function of the form:

$$F(C) = \sum_{t=1}^{T} D_{b,l}(t)$$ where $D_{b,l}(t)$=distance between box and centre

The evolved controller was given by:

```
(PROG
(OR (OR (>=0.62 LDR5)(OR (>=IR6 LDR3)(>=0.62 LDR))
(AND (>=LDR6 LDR7)(>=LDR3 LDR7))))
(AND (>=LDR3 LDR7)(OR (OR (>=LDR5 LDR3)(>=LDR3 0.62))
(>=LDR6 LDR7))(AND (NOT (>=IR6 LDR4))(>=LDR3 LDR7))))))
```

This controller first activates box side circling to move along the side of the box and then switches to box pushing to push the box forward. Box side circling is then activated again.

Genetic programming has also been applied to the automated design of analogue electronic circuits including both component topology and component sizing, including a low pass filter, a cross-over filter (woofer and tweeter), a 100 dB amplifier, a computational circuit for computing cube roots, a temperature sensing circuit, a voltage reference source circuit, and a time-optimal robot controller circuit [Koza et al 1997]. The process begins with a high level description of the circuit's behaviour – this is described by a system of integro-differential equations (one equation for each node or loop in the circuit according to Kirchoff's laws). The topology describes the number of components in the circuit, the type of each component (transistors, diodes, resistors, inductors and capacitors), and a list of all connections between components. The key is the mapping between genetic programming rooted, point labelled (acyclic) trees and line-labelled cyclic graph representation of electric circuits. Functions in the circuit-constructing program trees are divided into four categories:

(i) topology-modifying functions that alter circuit topology
(ii) component creating functions that insert components into the circuit
(iii) arithmetic-performing functions as arguments to component creating functions that specify component numerical values
(iv) automatically defined functions in function defining branches for re-use of circuit substructures

The starting point for the development of an electric circuit is an embryo which is a valid electric circuit that contains one (or more) modifiable wire, input/outputs, source and load resistors, etc. Architecture-altering operations are the key to the evolution of electrical circuits. Each program tree of the population creates one circuit. The electric circuit is evolved through the circuit constructing program tree containing a number of component-creating and topology-modifying functions. This inserts a component into the developing circuit. Modifiable wires are transformed into circuit components and connections. This represents a process of development. For the low pass filter, the fitness function is given by:

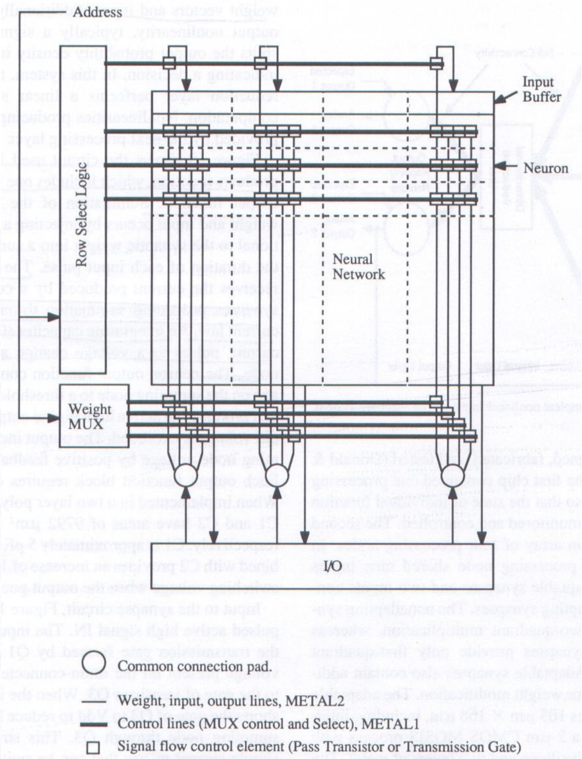
$$F(t) = \sum_{i=0}^{n} \left(W(d(f_i), f_i) d(f_i) \right)$$ where f_i=frequency of fitness case

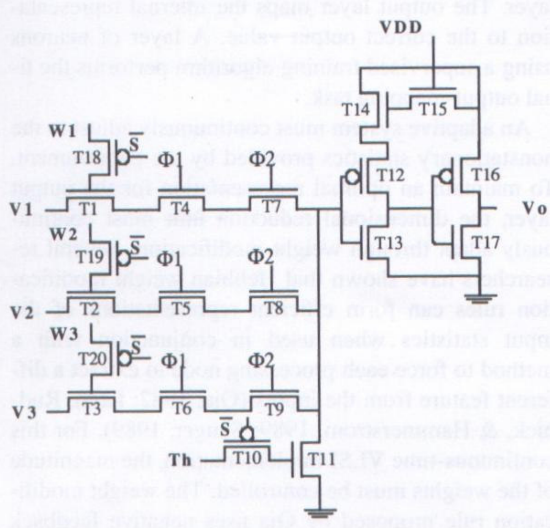
d(x)=absolute difference between target an observed values at frequency x
W(y,x)=weighting

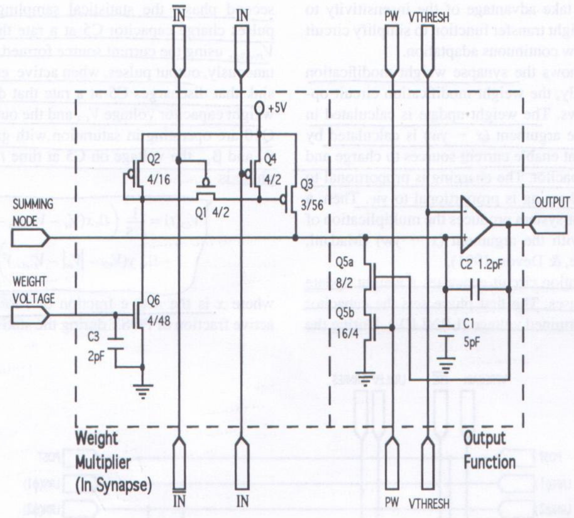
In all cases, population sizes were 640,000 members with 86.5% sexual reproduction, 10% asexual reproduction, 1% mutation, 2% branch duplication, and 0.5% branch deletion. The low-pass filter evolved resembled the Butterworth/Chebychev filter initially and separately a Cauer elliptical filter.

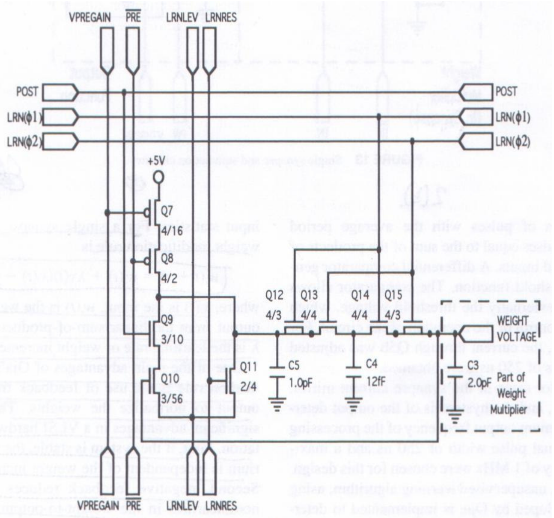
6.4. BIOMIMETIC COMPUTATIONAL HARDWARE

Biomimetic approaches to computation are generally based on neural network hardware architectures of mny interconnected simple processing units. VLSI offers high density component integration and simple recursive operations associated with pattern recognition have low Si area impact. In simple artificial neural networks, most nodes are connected to most nodes giving $O(n^2)$ connections – such high fan in/fan out connectivity is characteristic. For example, a 100,000 neuron network would have 10,000,000,000 connections. However, it is possible to generate highly layered, limited interconnection neural network architectures functionally similar to highly connected systems [Akers et al 1995]. One mode for achieving this is to model the network as a cellular array of cellular automata where each element is bidirectionally connected to all its nearest neighbours, rather than having loing distance connections like a neural network. The state of the element depends on those of its neighbours. Such networks behave as associative memories similar to neural networks. It is possible to segment the neural network into layers as different data sets may be introduced as inputs at different levels. Fault tolerance through spare rows and columns with error detection and correction codes provide for self-test and recovery.


Address
Input Buffer
Neuron
Row Select Logic
Neural Network
Weight MUX
I/O
Common connection pad.
Weight, input, output lines, METAL2
Control lines (MUX control and Select), METAL1
Signal flow control element (Pass Transistor or Transmission Gate)


VDD
T14
T15
W1
T18
S
Φ1
Φ2
T12
T16
V1
T1
T4
T7
Vo
W2
T19
T13
T17
V2
T2
T5
T8
W3
T20
V3
T3
T6
T9
Th
T10
T11


IN
IN
PW
VTHRESH
+5V
Q2 4/16
Q4 4/2
Q1 4/2
Q3 3/56
SUMMING NODE
OUTPUT
WEIGHT VOLTAGE
Q6 4/48
C3 2pF
Q5a 8/2
Q5b 16/4
C2 1.2pF
5pF
Weight Multiplier (In Synapse)
Output Function


VPREGAIN
PRE
LRNLEV
LRNRES
POST
LRN(Φ1)
LRN(Φ2)
+5V
Q7 4/16
Q8 4/2
Q9 3/10
Q10 3/56
Q11 2/4
Q12 4/3
Q13 4/4
Q14 4/4
Q15 4/3
C5 1.0pF
C4 12fF
C3 2.0pF
WEIGHT VOLTAGE
Part of Weight Multiplier

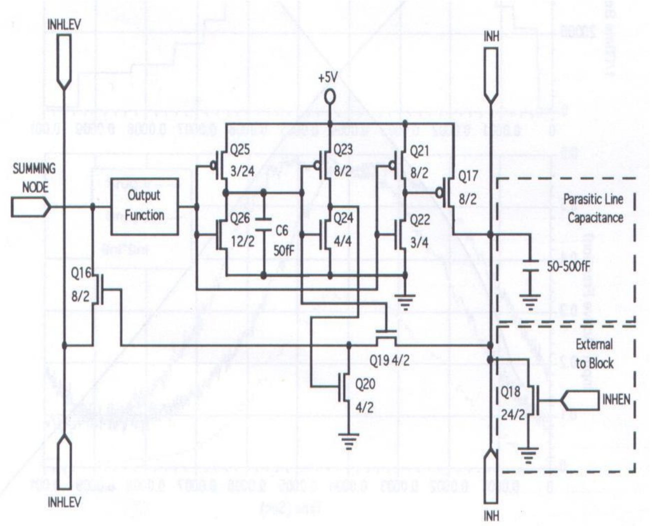


Fig 6-4 (a) Analogue synthetic neuron; (b) Chip architecture; (c) Single synapse and summation circuitry; (d) Weight modification circuitry; (e) Inhibition circuit [from Akers et al 1995]

6.5. NEURAL NETWORK HARDWARE

Human computers are capable of very high computation rates far in excess of that of biological creatures, yet cannot accomplish the simplest adaptive behaviours of even the simplest animals. A typical microprocessor consumes ~10^{-8} J/operation. Furthermore, current microprocessor integration of 0.1μ lies close to the limits of fabrication using current technology. Insects possess small brains of up to ~10^{6} neurons yet are capable of sophisticated sensory processing and behaviours. The human brain comprises ~10^{15} synapses with an average of 10 nerve pulses/s, ie. the brain computes ~10^{16} operations/s. Power dissipation within the brain is ~few Watts, so each operation costs ~10^{-16} J, ie. 10^{8} times more efficient than microprocessors – a microprocessor with the same computational power would dissipate ~100 MW.

Sparsely connected perceptrons such as a limited interconnect cellular neural system are more prone to local minima during training. Fully connected perceptrons with more signal paths find more easily near optimal solutions in weight space. A VLSI silicon neuron based on the heart interneuron of the leech has been developed – two such silicon neurons connected via inhibitory synapses have yielded a half-centre oscillator circuit [Simoni et al 2002]. It simulates seven ion conductaces which are summed onto a membraner capacitor – instantaneous Na+ current, persistent Na+ current, fast K+ current, persistent K+ current, slow Ca^{2+} current, hyperpolarisation current, and a leaky current. Membrane voltage is given by:

$$\frac{dV_{mem}}{dt}=\frac{\sum_{i=1}^{7}I_i}{C_{mem}} \text{ where } I_i = g_i m_i h_i (E_i - V_{mem})$$

g_i =maximum conductance

m_i =activation state$=\frac{1}{1+\exp(S_m(V_{mi}-V_{mem}))}$

h_i =inactivation state$=\frac{1}{1+\exp(-S_h(V_{hi}-V_{mem}))}$

E_i =reverse potential

Inhibitory synaptic current between the two silicon neurons:

$I_{inh} = g_{inh} s(E_{inh} - V_{mem})$ where s=0 for $V_{pre} < V_{thresh}$

$= \tanh(S_{inh}(V_{pre} - V_{thresh}))$ for $V_{pre} \geq V_{thresh}$

I_{inh}=inhibitory synaptic current

Analogue-digital synthetic neural circuit has been constructed whereby weights W1, W2 and W3 are stored dynamically on ther gates of transistors T1, T2, T3 [Akers et al 1995]. Only PMOS transistors (T18, T19 and T20) are used to pass weights. This circuit learns off-chip but for real-time processing and control, this is not practical. Pulse-coding provides robust and efficient processing. A set of delay lines and amplitude-sensitive neurons expand the dimensionality of the analogue signal. The tapped delay lines time-embed the input signals converting time information into a spatial representation required by the feedforward transfer function. A feedforward architecture comprises the sum of products between an input vector and weight vector as a measure of the match between weight vector and input. The summing node receives current produced by a complete row of synapses with summation through Kirchoff's current law. An integrating capacitor C1 converts current pulses to a voltage change at the summing node. The Oja unsupervised learning algorithm was implemented:

$w_i(t+\tau) = w_i(t) + \lambda y(t)(x_i(t) - y(t)w_i(t))$ where $x_i(t)$=input

$w_i(t)$=weight

$y(t)$=output from linear sum-of-products

λ=learning rate

Feedback from the neuron is used to normalise the weights. The synapse weight modification circuit computes the weight update by charging a capacitor in proportion to x and discharging in proportion to yw with a switched capacitir providing the final multiplication of y(x-yw). An array of neurons using a modified Hebbian weight modification rule requires a mechanism to force each neuron to extract a different feature from the input. A lateral inhibition circuit uses a global signal and a gate circuit to allow the neuron with the greatest sum of products to inhibit all the other neurons in the array. An analogue neuron has similarly been constructed to emulate the biophysical properties of real neurons [Douglas & Mahowald 1995]. It was constructed from a tree of compartments, each containing a capacitor to represent the membrane capacitance, a resistor which represents the axial resistance, and a set of voltage-sensitive conductances to represent ion permeable channels.

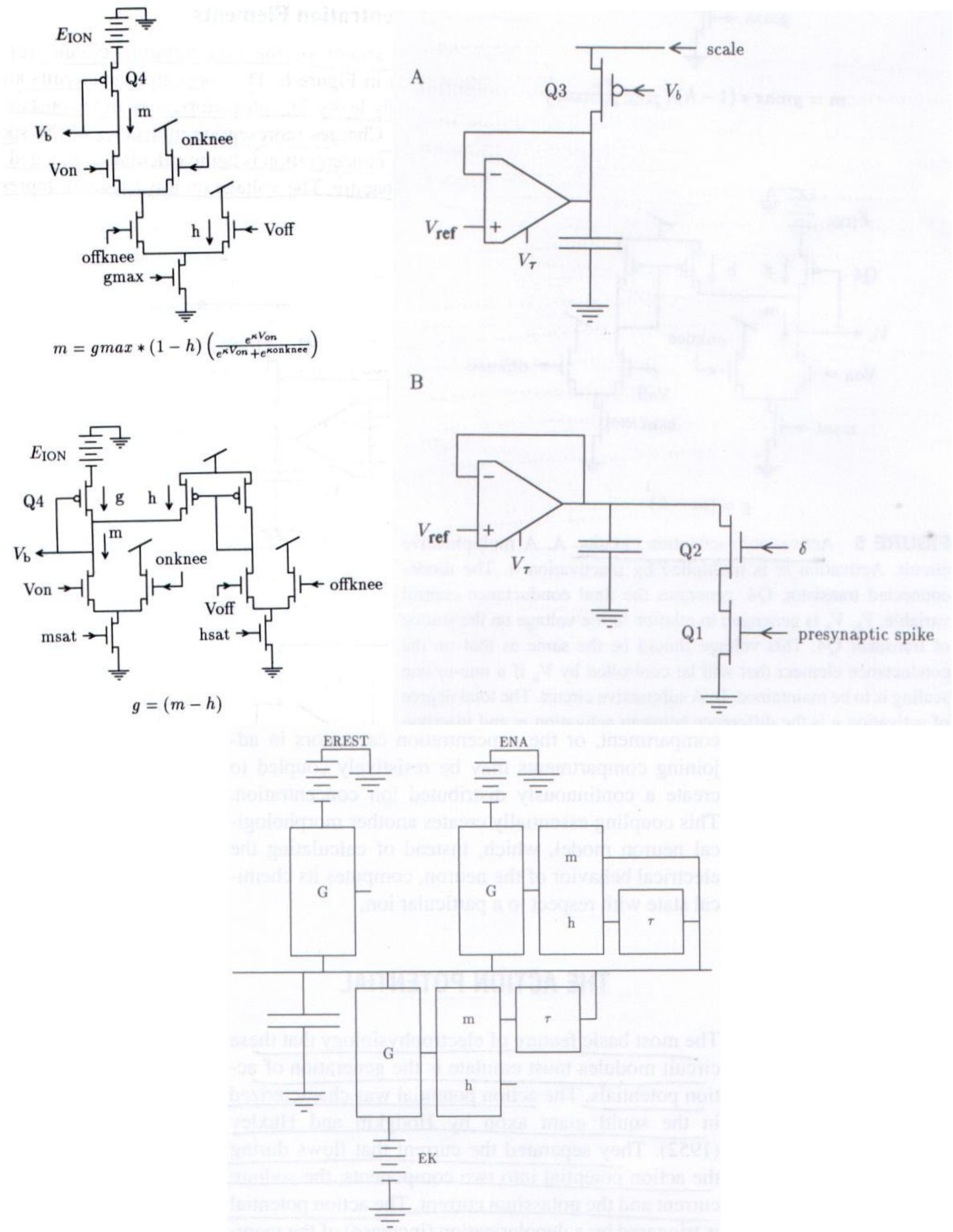


Fig 6-5 (a) Activation/inactivation circuits – a multiplicative circuit and substractive circuit; (b) Concentration circuits – intracellular ion concentration computed by a leaky integrator and synaptic neurotransmitter concentration by capacitor; (c) Si neuron comprising leakage conductance, Na conductance and K conductance [from Douglas & Maholwald 1995]

Each compartment provides a leakage conductance across its membrane which drives the membrane potential. The fraction of charged membrane channels that are open is determined by: $^{O}/_{(O+C)} = \frac{1}{(1+e^{-zVm/kT})}$ which defines the logistics relation between ion conductance and membrane potential. Conductances could be excitatory, inhibitory or shunting which coupled the membrane capacitor to a battery (current source). The transconductance amplifier conducts current onto and off of the membrane capacitor symmetrically around the ionic potential. The neural modules act as first order low pass filters which are concatenated to form higher order filters. A leaky resistance capacitance (RC) integrator is constructed from a transconductance amplifier and a capacitor whose time constant is varied by altering the transconductance of the amplifier. The activation/inactivation circuit implements the logistic relation between membrane voltage and membrane ion conductance through a differential pair circuit. The concentration circuit acts as a leaky RC integrator which measures neurotranamitter concentration at a synapse and the ion concentration within the cell. The action potential is triggered by a depolarisation of the membrane voltage generated by an external current source. These circuits may be combined to yield silicon neurons. Chen & Chen (2002) presented an evolvable biologically inspired artificial neuromolecular (ANM) architecture implemented on digital circuits. The input-output behaviour of the neuron is controlled by complex internal dynamics. ANM is an artificial network of neuronal modules with internal dynamics modelled by cellular automata.

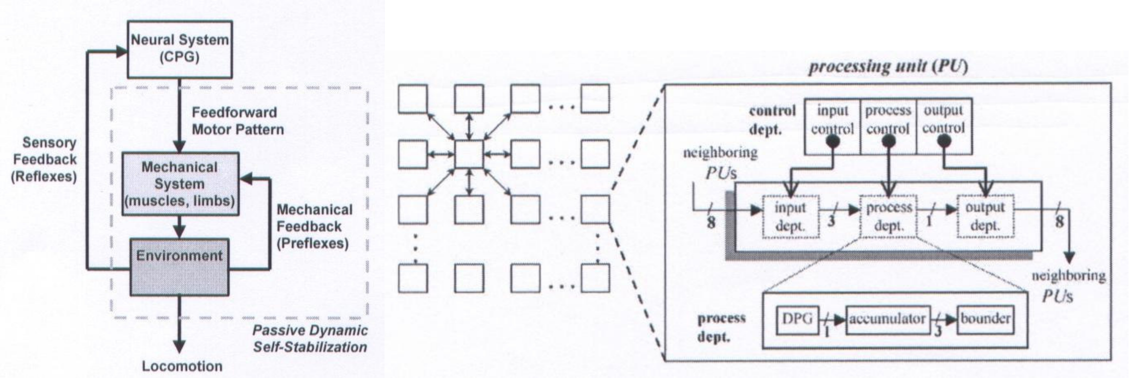


Fig 6-6 (a) Role of feedforward motor patterns, preflexes and sensory feedback; (b) Architecture of a cytoskeletal neuron [from Chen & Chen 2002]

Evolutionary search occurs at the intraneural level in the cytoskeletal structures responsible for the integration of signals. It is reckoned that cytosketal microtubules/microfilaments (eg. actin)/neurofilaments influence ion channels by the secretion of cAMP. Evolutionary learning at the cytoskeletal pathways alters the characteristics of neurons. Cytokeletal dynamics were simulated with 2D cellular automata and subjected to evolutionary learning on the neuron. Bode et al (2001) implemented Kohonen's self-organising map (SOM) in hardware based on a thyristor-based analogue-digital hybrid circuit. The hardware comprised a global controller circuit and a number of neuron units.

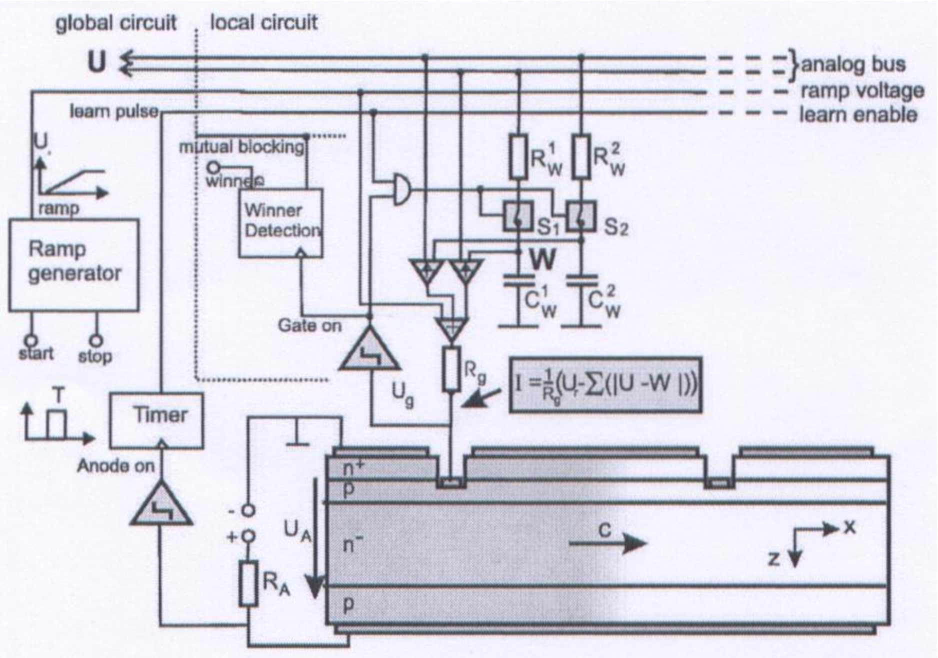


Fig 6-7 Hardware Kohonen self-organising map single gate neuron [from Bode et al 2001]

Each neuron unit stores one prototype vector, compares it to the input vector and outputs a distance as a fitness value and compares it to a common threshold. The units are connected to a multi-gate thyristor – each unit can turn on the thyristor locally and the change of state is propagated through the device to other neurons with delays (delay quantifies cortical distance). The winner-take-all strategy disables all competitors. The learning rule is typical of the SOM:

$w_{i+1} = w_i + \varepsilon f(d_{ij})(u - w_i)$ where $0<\varepsilon<1$

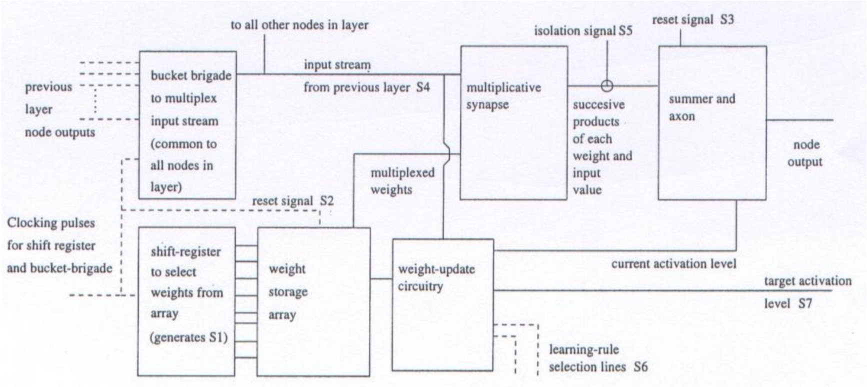
$h(d_{ij})$=unimodal neighbourhood function
d_{ij}=distance between unit I and winner j with max at i=j

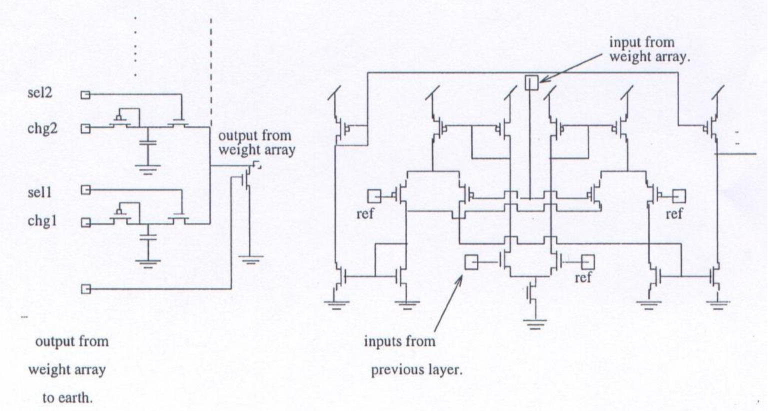
For learning vector quantisation (LVQ), $h(d_{ij})=\delta_{ij}$.

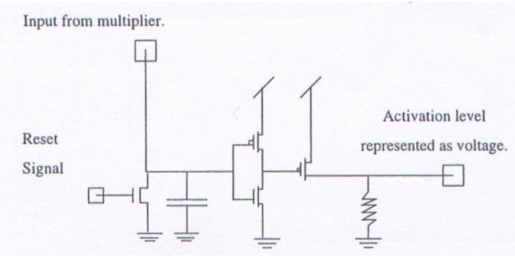
If learning rule is in continuous form: $\frac{dw_i}{dt} = \varepsilon(u - w_i)$

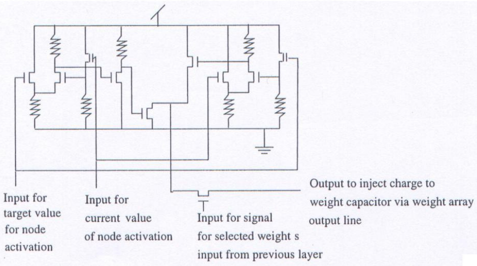
This differential equation can be modelled by charging of capacitor in RC circuit with $\varepsilon=(RC)^{-1}$. In Kohonen's SOM, learning rate depends on the distance to the winner neuron. This distance is determined by the propagation time of the signal.

An analogue implementation of a neuron using VLSI technology with both delta rule and error-corrective learning has been developed [Neal 2000]. This modular design included blocks for weighted synapses, summing and transfer function section, and weight update circuitry (for implementing the delta rule).


to all other nodes in layer
isolation signal S5
reset signal S3
previous layer node outputs
bucket brigade to multiplex input stream (common to all nodes in layer)
input stream from previous layer S4
multiplicative synapse
succesive products of each weight and input value
summer and axon
node output
multiplexed weights
reset signal S2
Clocking pulses for shift register and bucket-brigade
shift-register to select weights from array (generates S1)
weight storage array
weight-update circuitry
current activation level
target activation level S7
learning-rule selection lines S6


sel2
chg2
sel1
chg1
output from weight array
input from weight array.
ref
ref
ref
output from weight array to earth.
inputs from previous layer.


Input from multiplier.
Reset Signal
Activation level represented as voltage.


Input for target value for node activation
Input for current value of node activation
Input for signal for selected weight s input from previous layer
Output to inject charge to weight capacitor via weight array output line

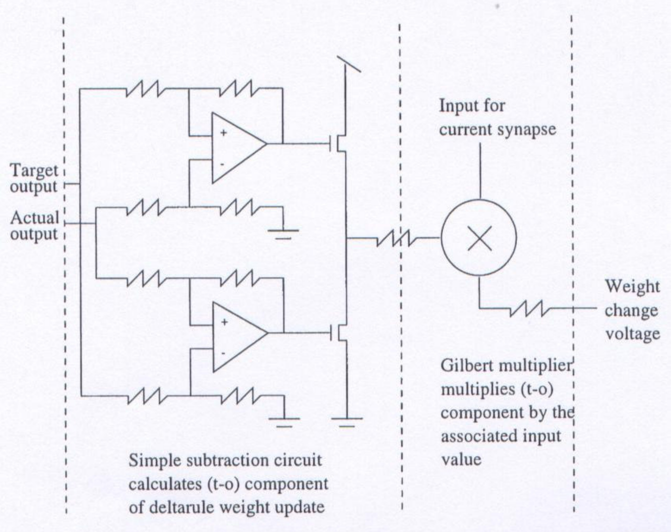

Target output
Actual output
Input for current synapse
Weight change voltage
Gilbert multiplier multiplies (t-o) component by the associated input value
Simple subtraction circuit calculates (t-o) component of deltarule weight update

Fig 6-8 (a) Functional decomposition of neuron; (b) Capacitor array and multiplicative synapse; (c) Axon; (d)Weight update circuitry for simple error correcting learning rule; (e) Weight update circuitry to implement delta rule [from Neal 2000]

A single Gilbert multiplier unit allowed serial encoding of the inputs with the outputs stored in a capacitor which represents the sum of products of the weights (a voltage divider resistance network and an operational amplifier) which is output to the axon (a three transistor amplifier which performs a sigmoid function operation).

JPL's 64x64 mask neural network chip has a mass of 5g, an area of 1 cm x 1 cm, low power consumption of 12 mW and programmability.

It is important to note that single neurons are not the unit of neural processing – neural assemblies are [Freeman & Shimoide 1995]. Such assemblies comprise interconnected networks of 10^4–10^5 neurons, each connected to 10^3–10^4 other neurons. Each neuron fires under 10 pulses/s and each firing is followed by a refractory period.

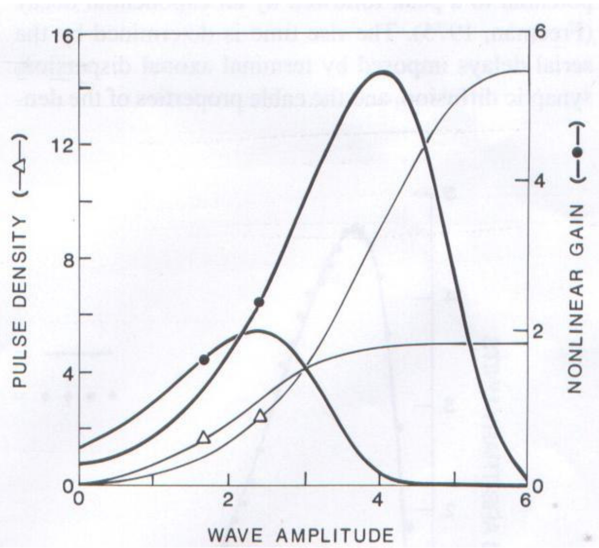


Fig 6-9 Biologically derived sigmoid function relating pulse density p to wave density v is asymmetric about its rest point [from Freeman & Shimoide 1995]

Such assemblies resemble cortical columns. Each local population of neurons receives axonal inputs and converts these pulses into dendritic current and sums the current within the cell body. A biologically derived sigmoid function relating pulse density p to wave density v is asymmetric about the rest point with the steepest point of the slope (dp/dv) lying on the excitatory side of the rest point. The steepness is determined by Q_m=5-12 in the cortex. The slope of the sigmoid function is given by:

$$Q = Q_m\left(1 - e^{-(e^v - 1)/Q_m}\right) \textit{for } v \le -u_0 ,$$

$$\boldsymbol{Q=-1} \qquad \textit{for } v \le -u_0$$

$$u_0 = -\ln\left(1 - Q_m . \ln(1 + 1/Q_m)\right)$$

$$p = u_0 (Q + 1)$$

$$\tfrac{dp}{dv} = u_0 e^{(v - (e^v - 1)/Q_m)}$$

Artificial neural networks (ANN) support the connectionist model of parallel computation and large virtual ANN's can be implemented with 10^9 interconnections and 10^6 processing elements on a single chip with VLSI technology. RAM-based FPGAs are particularly suited to implementing neural network hardware with different topologies, eg RRAN (real-time reconfigurable artificial neural network) implemented on Xilinx XC3090 FPGAs [Eldredge & Hutchings 1994]. RRAN divides the backpropagation algorithm into sequential execution of three stages – feedforward stage takes input patterns and propagates it through the network to generate an output; backpropagation stage computes output errors and propagates them backward through the network; update stage computes weight updates.

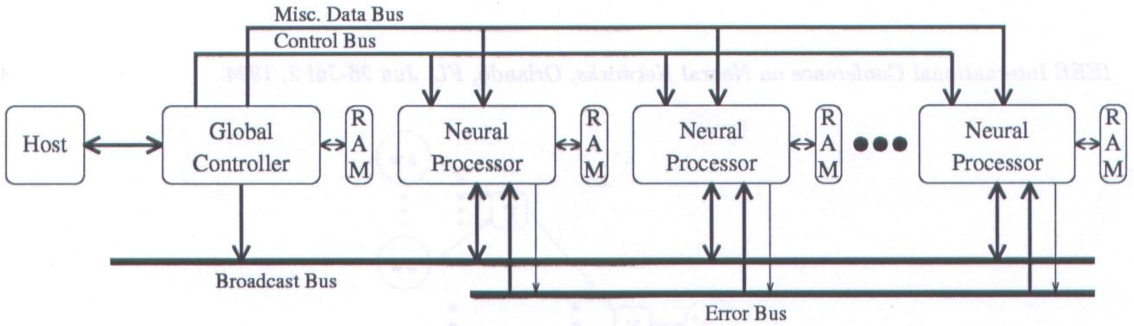


Fig 6-10 General RRAN architecture [from Eldredge & Hutchings 1994]

A global controller sequences processes for the neural processors, each of which contain 6 hardware neurons and a local RAM for storing weights and outputs. To reduce circuitry requirement of synaptic connectivity, look-up table architecture of FPGAs may be exploited [Bade & Hutchings 1994]. Specifically, the configurable logic block used to implement logic functions as 32-bit lookup tables is used to implement two synapses as a single Boolean function of four variables.

Large scale evolvable hardware for evolving complex digital circuits is based around a three dimensional array of 72 densely interconnected XC6264 FPGAs, each containing 16,384 fine-grained reconfigurable functional units and 512 reconfigurable I/O blocks [Korkin et al 2000]. The pattern of connectivity forms a three dimensional array of 6 x 4 x 3 FPGAs. Each invidual FPGA connects to its 6 neighbours usig bi-directional connections: 48 north, 48 south, 32 west, 32 east, 24 top and 24 bottom connections. Each of the 72 FPGAs has external connections to a 32-bit databud, an 18-bit address bus and a number of control lines to access the FPGA configuration registers. CBM supports both gate-level and function-level evolution. Each FPGA's internal logic is configured as a 3D cellular automata block of 4 x 6 x 8 cells, each cell connecting bdirectionally to its 6 neighbouring cells. Similarly, each FPGA connects to its neighbours. Each of the 72 FPGA modules contains a dedicated 16 Mb DRAM connected to the the FPGA through a 32-bit databus forming a 1.2 Gb distributed memory. Control is implemented through a SIMD strategy so each FPGA receives identical addresses and control signals. A dedicated CPU with 2 Mb SRAM controls all hardware resources. This has been used to evolve cellular automata based neural network of 75 million neurons (CAM-Brain machine). The evolutionary process uses a genotype-phenotype mapping to emulate embryonic growth. A complete chromosome comprises a string of growth instructions for each cell of the cellular automata array (typical instructions include move south, grow straight, split west and north, etc). A neural network is grown according to the chromosome and saved in DRAM which represents the 3D topological phenotype. A population of 1024 neural networks can be grown. Crossover and mutation operations are applied for evolutionary selection (by rank selection with elitism). Fitness is implemented by comparing the response to a desired response for a set of stimuli. The CAM-Brain represents the most sophisticated neural network ever built.

7. Onboard Control Systems

7.1. INTRODUCTION

The Attitude Determination and Control System of a spacecraft is responsible for orientating the body of the vehicle and maintaining stability even in the presence of external disturbances. The vehicle automatically determines its current orientation with respect to a reference frame and displays it. If the vehicle does not have the required attitude then the guidance system sends a correcting signal to the control system which actively controls the vehicle by manoeuvring it to achieve the required attitude. A body in space is subject to disturbance torques- either cyclic or secular- that reorient the vehicle. An ADCS system resists these toques either passively, by exploiting inherent inertia or magnetic properties to make the disturbances stabilising and their effects tolerable, or actively, by sensing the resulting motion and applying correcting torques [Wertz & Larson 1992]. The figure below shows a block diagram of a spacecraft's attitude control system:

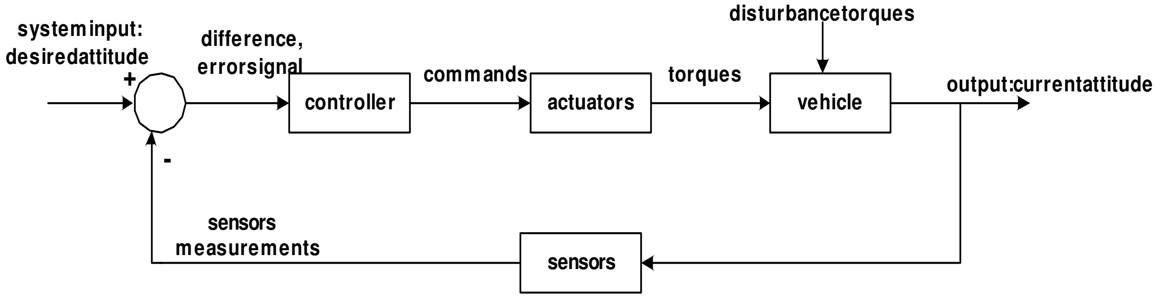


Fig 7-1: Spacecraft control system

Passive stabilisation techniques take advantage of basic physical principles and naturally occurring forces by designing the spacecraft to enhance the effect of one force while reducing others. In effect, disturbance torques are used to control the spacecraft choosing design to emphasize one and mitigate the others. A basic passive technique is that of spin stabilisation where the intrinsic gyroscopic 'stiffness' of a spinning body is used to maintain its orientation in inertial space. If no external torques are experienced, the angular momentum vector remains fixed in space, constant in both direction and magnitude. An energy damper will remove any nutation angle that may be present so that the spin axis and the angular momentum vector are coincident.

Passive control achieves low accuracy and therefore active control is mainly employed. The process generally involves measurement of the attitude of the satellite with respect to external references, determination of the attitude with respect to the local coordinate system, computation of the actuator commands, execution of the corrections by means of actuators mounted on the vehicle, and evolution of the attitude in accordance with the satellite dynamics under the effect of actuating and disturbing torques. The system can operate in closed loop on board the satellite. The actuators are controlled by the on- board equipment according to the sensor outputs. In more detail, the basic concept of active control is that the satellite current attitude is measured and compared with a predetermined desired value. The difference between the two, the error signal, is used to determine a corrective torque manoeuvre which is then implemented by the actuators. Since measurements and corrections cannot be perfect the cycle will continue indefinitely trying to minimise the difference between the desired and the actual measurements.

The attitude control actuators generate the necessary correcting torques to compensate for the external disturbances. Reaction wheels are torque motors with high inertia rotors. They have a nominally zero speed and may be rotated in either direction to provide one axis of control for each wheel. The spacecraft must carry at least one wheel per axis for full attitude control. The motor drives the wheel in response to a correction command as computed form the feedback control loop. Momentum wheels are reaction wheels with a nominal spin rate above zero to provide a nearly constant angular momentum. This momentum provides gyroscopic stiffness to two axes while the motor torque may be controlled to precisely point around the third axis. For high torque applications control moment gyros may be used instead of reaction wheels. A control moment gyro consists of one or more spinning wheels each mounted on gimbals which allow them to rotate freely in all directions. Turning the gimbal axis a high output torque, dependent on the speed of the rotor and the gimbal rate of rotation, is generated in any of the three orthogonal axes of the spacecraft. Magnetic torquers may also be used in space vehicles. Essentially they are magnetic coils that generate magnetic dipole moments. They generate torque proportional and perpendicular to the Earth's magnetic field and can compensate for the spacecraft's residual magnetic fields or minor attitude drift. Finally, thrusters produce torque by expelling mass and are note governed by the same concept as the momentum devices. They produce torques and forces that control attitude, manoeuvre the spacecraft over large scales, adjust orbits, dump extra momentum form a momentum wheel, reaction wheel or control moment gyro, control the spin rate and control spacecraft nutation.

The following table shows some typical ADCS actuators:

Actuator	**Typical Performance Range**
Thrusters:	
Cold gas	0.5- 9000 N
Hot gas (hydrazine)	< 5N
Reaction and Momentum Wheels	0.4- 400 Nms for momentum wheels at 1200 to 500 rpm: max torques from 0.01 to 1 Nm
Control Moment Gyros	25 to 500 Nm of torque
Magnetic Torquers	1 to 4000 Am^2

The current orientation of the vehicle should be determined with respect to a fixed coordinate system. Spacecrafts use sensors to determine their attitude and send appropriate signals to the control system. Inertial Measurement Units use sensors that measure rotational velocity using gyros and translational motion using accelerometers. Gyros and accelerometers are usually mounted on a gimballed platform which has a fixed inertial position so that all measurements are taken with respect to the same frame. An alternative to the heavy and complex gimballed platforms is the strapdown configuration in which the output of the body- referenced sensors is translated into an inertial frame using sophisticated software rather than having gimbals. Sun sensors use photo-voltaic elements which produce current when illuminated by the sun. They measure one or two angles between their mounting base and incident sunlight. They can be used as part of the normal attitude determination system, part of the initial acquisition or failure recovery system, or part of an independent solar array orientation system. Earth sensors measure infra- red radiation which is almost uniformly emitted from the Earth, by means of a thermosensitive element which enables detection of the contour of the Earth. Star sensors are the most accurate reference sensors in common use for measuring attitude. They measure the spacecraft's attitude with respect to known star locations. Then they compare these measurements to accurate maps of the brightest stars stored in the spacecraft's memory. The angle between the known star's position and a reference axis on the spacecraft helps determine the spacecraft's inertial attitude. Magnetometers measure the magnitude and direction of the Earth's magnetic field, and comparing it with the known values determines the attitude of the spacecraft. Their accuracy though is not as good as that of the star sensors since the magnetic field of the Earth is slightly varying with time and cannot be very accurately measured.

Sensor	**Typical Performance Range**
Inertial measurement unit (gyros and accelerometers)	Gyro drift rate= 0.003°/hr to 1°/hr Accelerometer linearity= 1- 5x10^{-6} g/g^2 over range of 20 to 60 g
Sun sensors	Accuracy= 0.005° to 3°
Star sensors	Attitude accuracy= 1 arc sec to 1 arc min 0.0003° to 0.01°
Horizon sensors: Scanner/ Pipper Fixed head (static)	Attitude accuracy: 0.1° to 1° (LEO) <0.1° to 0.25°
Magnetometer	Attitude accuracy= 0.5 to 3°

The focus in this report is in robotic planetary explorers but many of the technologies described in this section will be applicable to general spacecraft control systems.

7.2. INTELLIGENT CONTROL ARCHITECTURES

The problem of control in the real world is ill-posed, ie. the conditions of stability, uniqueness and solvability are not in general satisfied [Meystel 1988]. Any intelligent machine requires goals which defines its motivation encoded as functional requirements. Its effectiveness is determined by the level of success in the achievement of its goals. For this a sophisticated control system is required which maps its perceptual inputs to it output actions or behaviours [Kim 1989, Kaelbling 1991]. Any intelligent autonomous control system must utilise both robust and adaptive approaches, extensive decision-making capabilities and tolerance to failures. It should exhibit high efficiency, high reliability, good and consistent performance, wide operating ranges and evolutionary improvement over time.

Evolutionary robotics emulates biological processes – indeed, organisms interact with their environment which provides the selection mechanism for evolution. Organisms are in fact protein-based robots which carry self-replicating molecules. Hence, evolutionary robotics requires dynamic interaction with the real world (situatedness) through a body (embodiment) in order for effective control systems to evolve [Nolfi & Floreano 2002]. The control system and body morphology are tightly related, eg. in crickets, the hearing organ morphology defines their operation as auditory filters. The principles of design of mobile robotics are based on cheap design, redundancy and ecological balance – cheap implies ecological balance while redundancy suggests how ecological balance may be achieved. It is essential to consider the physics of the robot and its environment – behaviour is an emergent property of motor interaction with the environment and the history of this interaction. The agent and environment represent a coupled dynamical system – the state of one system fixes the state of the other and vice versa so that their parameters are dependent on each other. Each motor actions has two resultant effects: (i) actions determine how well tasks are performed; (ii) actions determine the next sensory patterns of the environment. Value systems are essential for autonomous robotics in order to assess detrimental and advantageous behaviours – it provides reinforcement of the learning process and motivational biases for behaviour. These biases are provided by reflexes which accelerate learning which rely on in-built sensory-motor patterns. All mobile robots require a number of predefined reflexes to avoid obstacles, retreat from collisions, turn towards attractive signals and general forward movement in the absence of stimuli. Braitenberg vehicles exhibit simple reflexes, the simplest being Braitenberg type 1 vehicle which possesses one sensor and one motor directly connected such that the higher the sensor activation, the faster the motor runs. Simple neural networks can be used for control systems: it has been shown that the XOR function is performed poorly by animals as it represents a situation rare in nature. The control system may be a neural network of three layers: a proximity layer, collision layer and a motor action layer. Each proximity sensor is connected to a node of the proximity layer and requires continuous activation neurons; each collision sensor is connected to a node in the collision layer but requires only binary response neurons. The proximity layer is fully connected by Hebbian synapses to the collision layer. Hebbian learning has the form: $\Delta w_{ij} = \eta a_i a_j$ where $a_{i,j}$ = neural activation of neuron i,j – it states that when two neurons are persistently fired in conjunction with each other, then their association is increased. The collision layer is hardwired to the motor layer for the built-in reflexes. During a collision, a collision node and several proximity nodes will be activated, strengthening the corresponding connections through Hebbian learning. A subsequent similar event will yield greater activation. Eventually, the robot will learn to correlate and recognise proximity cues before collision and thereby avoid obstacles, ie. it will learn to anticipate collision before it happens. It learns through simple associative Hebbian learning due to redundant overlap of information from collision and proximity sensors. The input to the node i in the collision layer:

$u_i = c_i + \sum_{j=1}^{n} w_{ij} x_j$ where x_j = node j activation in proximity layer such that $0<x<1$

w_{ij} = weight between proximity node j and collision node i
c_i = 1 for collision
= 0 otherwise

Activation of collision node i, $a_i = f(h_i) = 0$ for $h_i < \theta$
$= 1$ for $h_i \geq \theta$

Weight change is given by: $\Delta w_{ij} = \frac{1}{N}\left(\eta a_i x_j - \varepsilon \bar{a} w_{ij}\right)$ where $\bar{a}$ =average collision layer activity
η=learning rate

Term $\bar{a}$ implements active forgetting to prevent large weight values and so reduce overgeneralisation. The conditioned stimuli (CS) are the proximity sensors which learns the conditioned response (CR) by association with the unconditioned stimulus (UCS) of collision sensors which yields the unconditioned response (UCR). In this case, CR and UCR are identical behaviours. Leaky integrator neuron offers the addition of a decay term within the activation function which solves the problem of oscillation of the activation function by acting as a low pass filter [Scheier & Lambrinos 1995]:

$a_i(t) = \tau a_i(t-1) + e^{(1/2)(w_i(t) - x_i(t))^2}$ where $a_i(t-1)$=activation of previous timestep
τ=neuron time constant

$x_i(t)$=input

Control systems, like their biological counterparts, interact with their environments. The physical embodiment of the control system (its body) provides a buffer between the external environment and the control system (its brain). Sensors receive emissions from the world environment which are input to the control system. The control system sends signals to the effectors to perform actions which affect the state of the world. The body essentially provides a medium between the environment and the control system [Fritz 1989]. Dreyfus (1967) suggested that physical embodiment is a necessary prerequisite for intelligent behaviour and that disembodied computing systems as used in traditional artificial intelligence will never exhibit truly intelligent behaviour. The primary goal of an intelligent system is survival and self-preservation. Behaviour determines the actions which help to attain those goals. The environmental nature of cognition through perception and action are an integral part of cognitive processes – concepts cannot be context free. The pleasure/pain principle determines the riteria for selecting actions with the pleasure level corresponding to the closeness of of goal attainment, ie. pleasure acts as an evaluation function. To achieve its primary goal, the intelligent control system must have the following properties [Fritz 1989]:

(i) it receives sensory data from its environment to determine the present state of the environment – this is critical in uncertain environments;
(ii) it chooses subgoals in accordance with its overall goals;
(iii) it constructs plans of action based on previous experiences to attain its subgoals;
(iv) it executes those plans;
(v) it must learn at all times.

Feather (1967) suggested that intelligent behaviour is information-seeking such that information from the environment is selectively analysed for consistency with previous knowledge. This defines its usefulness and reinforces the paradigm that intelligence is an information processing concept. Intelligent machines re characterised by a sophisticated world model of the environment. Representation of self is also necessary within the world model in order to model limitations of the agent with respect to its goals. This world model should also be geared towards objects in the real external world that are operationally (biologically) important. Such limitations in the world model are essential due to the high complexity of the real world environment. Simplified representations of problems and applied constraints provides the basis for adequate rather than optimal behaviour within a complex world – this is bounded rationality (satisficing). Biological perception has evolved to limit the vast amount of information available in the external environment that is processed within brains.

A modular layered hierarchical control structure provides a reduction in complexity at each level but an increased time constant. Low level functions implement real-time control with fast response times (eg. ~10^6 MIPS) while higher levels implement cognitive function with slower response times (eg. ~10^2 MIPS) [Moravec 1984]. Higher levels require less precision but greater temporal and contextual horizons. Commands flow from higher levels to lower levels wheras response information flows vice versa. Imprecision characteristic of higher levels arise from incomplete a priori information in unstructured and uncertain environments. Total entropy provides a measure of uncertainty which must be minimised by the control system hierarchy [Saridis 1984, Valavanis & Saridis 1985]. If system complexity is defined as the maximum information transmission gain rate of the system (its channel capacity), there exists a minimum complexity of the control system for a given environmental uncertainty [Pandelis 1990]. Given that intelligence may be regarded as the ability to acquire and process knowledge (structured information), the flow of knowledge to reduce uncertainty (entropy) must satisfy Jaynes' principle of maximum of entropy. Optimisation consists of minimising the total entropy by increasing knowledge throughput rate. Sloman & Croucher

(1981) proposed that the human mind architecture comprises a central administration processing unit which behaves as an overall operating system. A motive-generator within this adminstration unit provides goals and preferences while motive comparators assign priorities to resolve motivational conflicts. Satisfaction or violoation of such motives generate emotion. Failure generates “pain” and invokes corrective action. Satisfaction of motives generates pleasure. Meystel (1988) proposed a nested multiloop hierarchy with top down resolution refinement using successive approximations. Upper levels with their low resolution of state have slower time scales for planning activities. The lower levels with their high resolutions of state have faster time scales for dynamic activities. There is a gradual change from offline planning to online real time control. Although at all level there are independent control loops vertical links connect the levels to provide consistency of overall operation. The 3 level hierarchy was referred to as the Planner-Navigator-Pilot hierarchy with perception-plan-actuation control legs. The Planner-Navigator-Pilot levels were also linked horizontally at each level.

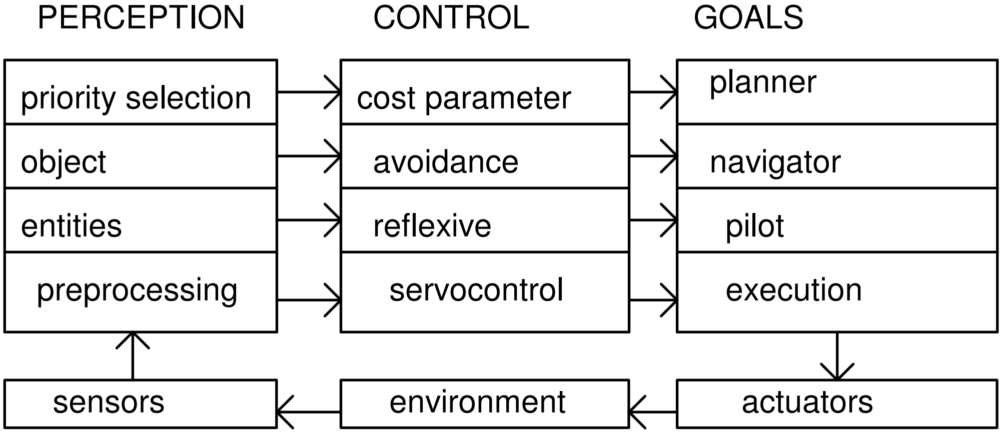


Fig 7-2: Planner-Navigator-Pilot hierarchy (from Meystel 1988)

Each lower level is constrained by solutions from the upper levels. At any level if constraints are violated on the basis of new environmental conditions and new information this new information should be submitted to the next upper level for updating to generate a new set of constraints. Planning is connected to control by intermediate decision making levels. The sensory hierarachy from the preprocessing level involves a sequence of zooming operations, ie. the focussing of attention to within the constraints of the limited computing power at each level. This is a form of recursive generalisation and such generalisations are required to efficiently use computing resources through attention. The knowledge based system is also hierarchically determined by resolution of representation. Sensory information flows up the hierarchy in bottom up data driven fashion while commands flow down the hierarchy in top down goal driven fashion.

During the late 1980’s, NASA had developed a baseline computational architecture to support space robotic systems and this envisaged gradual evolution from teleoperative mode towards autonomy (NASREM) [Albus, McCain & Lumia 1987]. Albus (1999)’s NASREM derivative model is an example of an intelligent robotic architecture. The first phase of evolution is that of the "intelligent aid" whereby automatic control of individual subsystems would be achieved. The "intelligent apprentice" stage follows when automatic control of multiple subsystems has been achieved. Next comes the "intelligent assistant" characterised by hierarchical control of multiple subsystems and finally the "intelligent accomplice" will be characterised by automated distributed control of multiple subsystems [Decker 1987]. At all stages, humans will have top-level authority, responsibility and control. This evolution towards autonomy will result in major reductions in ground segment costs which can be as high as ~60% of space mission lifecycle costs [Wertz & Larson 1988]. The communication time delay, bandwidth limitations and human performance limits will contribute to this evolution. Teleoperation requires high information flows and will force the use of computational techniques to be employed remotely. World modelling and sensory processing are decomposed into hierarchical levels which correspond and map onto each level of the control hierarchy. The world model hierarchy is resolved according to generalisation while the sensory processing hierarchy is decomposed as an attention focussing mechanism. Both resolution strategies act to limit computational overheads.

Most mobile robot systems have implemented a common blackboard database/world model type intelligent control system and NASREM is no exception [Levi 1987]. The blackboard model is inspired by cognitive psychology in that it essentially models aspects of human cognition: knowledge sources represent permanent long term memory while the blackboard represents short term working memory. Blackboard systems use multiple knowledge sources to analyse different aspects of a complex problem. The blackboard control architecture provides a uniform system which integrates a number of diverse, specialised and independent knowledge sources which communicate through a common global database (blackboard). The essence of the blackboard system which uses a common memory between multiple knowledge sources is that it provides the means for results sharing when subproblems cannot be solved by independent non-communicating agents. Different specialists contribute to different aspects of the plan which are posted to the blackboard and incorporated into the plan. All domain specific data (including partial solutions) are posted onto the blackboard by each knowledge source for accessibility allowing the broadcast of events to all the knowledge sources via the blackboard. A master control program examines the blackboard and schedules the component subsolutions into composite solutions. The blackboard is a high level operating system that integrates the control of the distributed component knowledge sources according to its "master" plan. An executive program controls the activation of each knowledge source in turn when an event occurs. The system goals determine the plan which specifies the tasks to perform and in which order according to priorities and time constaints. No individual agent can solve the problem alone so the blackboard acts as a shared global database to allow communication and cooperation. The agents are knowledge sources that can react to and modify the blackboard data structures. Each knowledge source comprises of procedural condition-action production rules for event driven processing. The knowledge sources are independent and autonomous yet allow simultaneous indirect cooperation amongst the knowledge sources through information in the blackboard. Each knowledge source is guided by strategic plans to provide metalevel control. Knowledge sources can modify posted plans based on subsequent contributions from other sources. Executive knowledge sources apply inference techniques to generate solution elements on the blackboard and knowledge sources respond to, generate, and modify solution elements on the blackboard. A set of solution elements on the blackboard constitutes a partial plan. Silverman et al (1989) used a blackboard system as a NASA testbed for autonomous ground control centre operations for spacecraft support. Typically the system would replace the ground facility manager, the spacecraft job scheduler, the facility operator and the repairman. Hearsay II is a blackboard continuous speech understanding system comprising a set of functionally distinct cooperating knowledge source experts which operate in parallel, a blackboard hierarchically divided into sound, word and sentence levels, a priority based task scheduler, and a focussing mechanism for metalevel control. Each knowledge source is knowledgeable about some aspect of language processing: syntax, semantics and lexical.

The NASA/NBS Standard Reference Model architecture (NASREM) for telerobotic control was developed as a logical and functional computing architecture for telerobotics in support of the Space Station programme with particular reference to the FTS (now cancelled) [Albus et al 1987, 1988]. It has since been adopted by ESA as their standard architecture for space robot systems. It may be implemented with the lower levels of the hierarchy performed onboard the spacecraft and the higher levels executed on the ground due to their greater temporal windows. It defines a set of computing modules and standard interfaces to allow the integration of telerobotic software without specification of each module's mode of operation. It provides the basic requirements for flexible control strategies involving both cognitive and reflexive behaviour. The central component is the world model blackboard since such knowledge representation will affect planning, control and sensing. It implies the manipulation of knowledge to provide context by integrating a priori sensory data with a posteriori knowledge base data. It is hierarachically structured into multiple layers: layer 1 is concerned with kinematic coordinate transformations; layer 2 performs the dynamic analysis and trajectory interpolation; layer 3 is concerned with path generation and obstacle avoidance; layer 4 transforms object tasks into specified sequences of elementary movements; layer 5 decomposes multiple actions and sequences and schedules individual tasks; layer 6 involves allocation of resources between distributed individual telerobots at different worksites according to mission priorities. Levels 1 to 3 are part of the low level control system (the operations performed by the cerebellum) which tend to be fixed while levels 4 to 6 are concerned with high level planning and are task specific and highly variable (the operations performed by the frontal cortex). NASREM is also horizontally partitioned into 3 processing legs comprising a distributed heterarchical structure (ie. multiple units at the same level of abstraction): the task decomposition (TD) leg performs planning operations; the world modelling (WM) leg represents the internal representation estimate of the external world and provides a simulation capability and includes knowledge sources pertinent to the task requirement; the sensory processing (SP) leg involves extracting information from the external world and processing sensory input data to update the world model and comparing observations with expectations. The output is provided by actuators and input by sensors. Albus (1991) later expanded the task decomposition leg into two systems elements called the behaviour generation modules and the value judgement modules. The value judgement system determined the reward/punishment values of the world and of predictions and made decisions on that basis – this included considerations of priorities, beliefs, and uncertainties. The behaviour generation system selected goals and plans and executed tasks. The goals provided the objective and the task execution provided the behaviour.

The sharing of data is horizontal such that more information flows horizontally at the same level than that which flows between levels. The flow of commands and status data is vertical: sensory processing is bottom up (data driven) and task decomposition is top down (goal directed) though the world model can act as an expectation generator for goal directed sensory processing and as a feedback mechanism for task decomposition to allow monitoring and provide data driven control. The hierarchical levels are defined by temporal and spatial decomposition of tasks into finer levels of resolution through a "chunking" process – the control bandwidth decreases by an order of magnitude at each higher level. The sensory processing modules filter sensory data from multiple sources, detect and recognise patterns in the environment. Data from multiple sources must be unified into a single representation scheme in the world model (sensor fusion). Perception comprises comparing sensory observations with expectations generated by the internal world model which is a unified estimate of the state of the external world. The world model includes a database and a simulation capability to generate expectations and predictions. Task decomposition selects and analyses goals and plans and executes tasks. Tasks are decomposed recursively into subtasks and sequenced to achieve the desired goals. The world model predicts the result of plans and the task decomposition modules select plans on the basis of the state of the world and the results of the hypothetical plans. Each SP module comprises 4 submodules: a comparison matcher to match observed data with the world model predictions, temporal integrator to integrate differences and similarities of observations and predictions with time, a spatial integrator to integrate data over space and a recognition thresholder which defines that when a correlation function exceeds a threshold recognition occurs. Hence the SP and WM modules are coupled to form a feedback loop and the merging of SP and WM data forms an adaptive resonance process. Level 1 comprises brightness/colour intensities and their derivatives at each pixel; level 2 comprises connected edges and vertices (Marr's primal sketch); level 3 consists of textures, orientations, shape, size and boundaries (Marr's 2.5D sketch); level 4 comprises 3D volumes and objects (Marr's 3D model); level 5 comprises groups of objects and their relationships to each other; level 6 comprises the total environment.

The task decomposition modules comprise one job assignment module and a set of planner and executor modules. They decompose the task goals both spatially and temporally into finer resolutions into plans of sequential and concurrent actions (possibly represented by AND/OR graphs). The job assignment manager partitions tasks into spatially distinct jobs to the planners and the planners decompose each job into temporal sequences of subtasks. The optimal plan is then selected according to its evaluation function. For each planner the executor executes and monitors the plan execution through feedback to provide reactive control. Reactive control required the SP modules to be directly linked to the TD modules to bypass the WM. The WM modules provide the interface between sensory processing and task decomposition such that the SP modules update the world model which in turn provides the context for the TD modules to plan. The WM comprises a hierarachical short term memory (STM) which effectively implements a "chunking" process. The WM makes predictions and evaluates current states and provides expectations of future states as a simulator. Knowledge in knowledge bases is used to generate task dependent knowledge and may include CAD models. The WM essentially comprises a "blackboard" such that it updates the knowledge base and provides data accessible to all other modules. The task information in the knowledge bases may be represented as frame data structures. The WM uses a posteriori knowledge (all ready known) from the knowledge bases and a priori knowledge (learned information) from the sensors. The global memory is a virtual database where knowledge about the internal state and current state of the world model is maintained. It is accessible to the world model and maintains the current best estimates of the state of the world. It is kept current by the world model. It includes cognitive maps to represent distributions of bodies in space at different resolutions, lists of objects, features, relationships (CAD models, topological trees, semantic nets, schemas, production rules). Global memory may be physically distributed but appears globally transparent.

The communications system routes data and messages between the modules to exchange information via the global memory either via bus or LAN. Traffic is clock-controlled such that there is a data-transfer/compute cycle whereby computed output variables at t=1 become available as input variables at time t=i+1. Data is conveyed from all output buffers mediated by flags to signify readiness to global memory/world model at the end of the compute cycle and thence to the input buffers representing information at the next cycle. The communication system should be aided by protocols to allow for event driven access to data and information. Although NASREM implements data exchange through the blackboard it is possible to extend the architecture to allow modules to exchange data directly amongst themselves also in a heterarchically distributed fashion, eg. contract net protocol. At different levels of the hierarchy different temporal synchronisations are required and perceptual resolutiuon decreases an order of magnitude at each higher level: at level 1, <ms; at level 2, ~ few ms; at level 3, ~1/10s; at level 4, ~few s; at level 5, ~minutes; at level 6, ~minutes to hours. Similarly higher bandwidth communication is required across hierarchical levels than for command/status traffic between levels. The control bandwidth decreases an order of magnitude at each higher level of the hierarchy. NASREM is completely open regarding its mode of implementation allowing connectionist architectures [Albus 1991].

7.3. BEHAVIOUR CONTROL

Anderson & Donath (1990) have suggested that animal behaviour rather than human cognition may be more appropriate as the basis for developing machine autonomy. There is little doubt that our cognitive system evolved froma primitive regulatory control system [Norman 1980]. De Beer et al (1990) observed that insects are capable of autonomously adapting a limited repertoire of basic behaviours to variations in the noisy complex environment of the real world. Innate behaviours are automatic and data driven in that they are generated by specific stimuli in the environmental situation which releases specific fixed action patterns. A rigid relation exists between the stimulus and response providing reflexive behaviour with immediacy. The required input stimulus to activate reflexive responses is much less than the total sensory information available. This minimal sign stimulus is guaranteed to evoke the response is mainly due to specialised stimulus recognition hardware which increases the speed of response. Such sets of innate behavioutr tend to be species-specific and geared towards self-preservation. Motivation is a form of goal generation and influences behaviour [White 1959]. Motivation is independent of inborn primary drives such as hunger (energy resuppy), sex (self-replication), and fear (self-preservation). Primary drives are strong when aroused, but can be sated. Motivation is internally generated and so is a function of internal state and is directed towards the environment. The tendency to exploratory behaviour in animals is an innate motivation on which learning is based. This brand of motivation is manifest as curiosity as a tendency to investigate objects in the environment – the object concept is central to play in young mammals as a manifestation of learning through model-building. It is selective and persistemt and cannot be sated: it can only decrease as familiarity induces habituation. It is a general state which gives way to stronger primary drives when they are aroused. Primitive behaviours should include:

(i) feeding drive (energy re-suppy) is the primary priority;
(ii) self-preservation drive through both freeze and avoidance behaviour;
(iii) exploration through attractive behaviour towards unknown objects;
(iv) goal directedness through attractive behaviour to primary motivations.

When primitive behaviours operate concurrently, complex higher level behavioural patterns emerge which are attributable to none of the individual behaviours alone. A collection of competing behaviours effectively generate a coherent pattern of emergent behaviour. To avoid the possibility of cyclic behaviour, memory must be incorporated to enable alteration of behaviours based on previous experiences. This is the basis of behaviour control.

Brooks (1989) implemented the behaviour based control system on a 1kg 6 legged robot with a length of 35cm (Genghis) as a network of 57 finite state machine processors. A typical processor is the MIT Media Lab miniboard 2.0 with an 8-bit Motorola 6811 neurochip CPU, 256 bytes of internal RAM and 12 kbytes of programmable ROM. Each leg was controlled separately and rough terrain was compensated by force monitoring in each leg. Whiskers anticipated obstacles and infrared sensors detected moving objects to which it was attracted. Robust walking behaviours were produced by the distributed system with little central coordination and it was capable of robust steering and target following. Collisionless navigation is thus achieved using simple computational processes. Hence, complex behaviours emerged from the network of simple behaviours with little central control. Planetary rover prototypes implementing behaviour control have been implemented in various forms, such as the Rocky series. Miller (1992a,b) developed ALFA, a programming environment comprising of networks of computational modules which communicate with each other, sensors and actuuators through dataflow communications channels. This allows the implementation of behaviour-based control through a programming environment. The US Sojourner rover and Mars Exploration Rovers adopted the behaviour control paradigm. These were implemented and tested on the Rocky series of prototypes. The Rocky 3 and Rocky 7 navigation algorithm was as follows [Volpe et al 1997]:

```
!ROCKY 3 & 7 NAVIGATION ALGORITHM
!Example parameters for the Rocky micro-rovers were:
!Nominal translation=0.25m
!Nominal rotation =0.5 rad
!Small orientation error=0.0<0.2 rad
!Medium orientation error=0.2<1.0 rad
!Large orientation error>1.0 radSmall position error=0.0<0.25m
!Medium position error=0.25<1.5m
!Large position error >1.5m

1.  LOCALISATION
    Measure global rover position from lander
2.  WAYPOINT
    Set new reference position from task queue
3.  TURN-TO-GOAL
    If position error is small
       Goto 1
    Else
        Turn in place towards goal
4.  OBSTACLE-DETECT
    Measure terrain in front of rover
5.  TURN-IN-PLACE
    If obstacles centre or left and right
        Turn nominal rotation right
    Goto 4
         If obstacles left/right
              If previous obstacles left/right
                   Goto 6
              Else
                   Turn nominal rotation left
                    Goto 4
6.  THREAD-THE-NEEDLE
    If obstacle centre
          Move total alley length straight backwards
          Goto 4
    Else if obstacles left or right
          Move nominal translation straight forward
          Increment total alley length
          Obstacle_detect
          Goto 6
    Else if obstacle clear
           Move nominal translation straight forward
           Goto 4
7.  LOOP-TO-GOAL
    If orientation error is small
          Move nominal translation straight forward
    Else if orientation error is medium
```

```
        Set turn radius to large
        Move nominal translation forward
Else if orientation error is large
        If position error is medium
            Goto 3
        Else
            Set turn radius to small
            Move nominal translation forward
Goto 4
END
```

Behaviour based control methodologies are ideal for low level online reactive behaviours to be invoked during plan execution to provide robustness to planning. However, behaviour-based techniques are insufficient by themselves. Malcolm & Smithers (1990) were also concerned with interfacing a Prolog planning system with a plan execution system of behavioural modules. The planner was grounded through a single hierarchy of behavioural modules with tight sensing and action coupling rather than with a twin hierarchy of sensing and action (eg. NASREM). Their SOMASS robotic assembly system comprised of a cognitive planner implemented in Prolog in hierarchical format which utilised dependency directed backtracking and a subcognitive plan execution system. The plan execution system was essentially charged with the function of handling the uncertainties of the real world. The more competent the plan execution system the less complex the plan needed to be. The subcognitive plan execution system was built from behavioural modules which encapsulated useful behaviours with certain functional capabilities. By handling uncertainty at a low level within the plan execution system, the planner was able to work in an ideal and certain world.

Spatial cognition must have arisen early in animal evolution as it is so basic for locomotion and nasvigation. Spatial cognitive abilities are simply scaled up versions of simple stereotypical behaviours by which four levels of spatial cognition were defined [Mallot 1999]. Level 1 behaviours are simple taxis responses such as attraction (foraging) and repulsion (obstacle avoidance). Braitenberg vehicles are simple vehicles with direct connections between two front sensors and two rear drive wheels. The best known is vehicle 3b in which each drive receives contralateral inhibitory sensory inputs. The sensors respond to stimuli and invoke avoidance as drives on the strongest side of the source respond faster, invoking a turning away of the vehicle from the source. The same mechanism within a corridor invokes centring behaviour. Level 2 behaviours require the addition of spatio-temporal integration of sensory data through interneurons to act as working memory to store home position required for path integration. Level 3 behaviours require long-term memory for learning of landmarks through plastic modification of spatio-temporal processing. Up to level 3, all behaviour is dependent solely on sensory inputs. Level 4 behaviour is characterised by goal-dependent behaviour such that behaviour is determined by both sensory input and current goal. Goal stacking requires declarative memory to plan routes – this is often referred to a cognitive map as a graph of recognition-triggered responses: nodes represent views while edges represent spatio-temporal connections between views. The cognitive map represents a mapping between the states of the organism and its location in space – this requires the use of landmarks as geometric features of the environment in order to select the shortest Euclidian distance between the current and goal positions. Hence, the cognitive map is a stored memory of landmarks representing geometric space to enable routes and paths to be selected [Bennett 1996]. It is of course augmented by path integration – dead reckoning – by optic flow and/or internal sensing. Egocentrically, this is represented as a vector from current or remembered situations but allocentric data is derived from computing a novel vector or route. The snapshot model matches its current retinal image of the environment with a stored library of 360^{o} snapshots of the environment [Cartwright & Collett 1983]. Associated with each snapshot is a vector towards the goal. This allows novel shortcutting by vector addition. Reid & Staddon's (1997) cognitive map was based on a diffusion model of the dynamics of stimulus across a set of interconnected units of the form:

$$\Delta V_q = \alpha \sum_{i=1}^{N} (V_i - V_q)$$ where N=number of neighbours=8 for 2D lattice

α=diffusion rate parameter, $0 \le \alpha \le \frac{1}{2}$
V_i=expectation associated with neighbouring units i
V_q=expectation associated with central unit q

At each time step, the system moves to the adjacent unit with the maximum expectation. Barriers reduce the number of active neighbours while stimulus increases expectation.

It is apparent that the hippocampus of the medial temporal lobe (and associated areas within the lobe including the amygdala and entorhinal, perirhinal and para-hippocampal cortex) plays an important role in memory function – indeed, there are multiple memory systems with distinct anatomical organisations and functionality [Squire 1992].

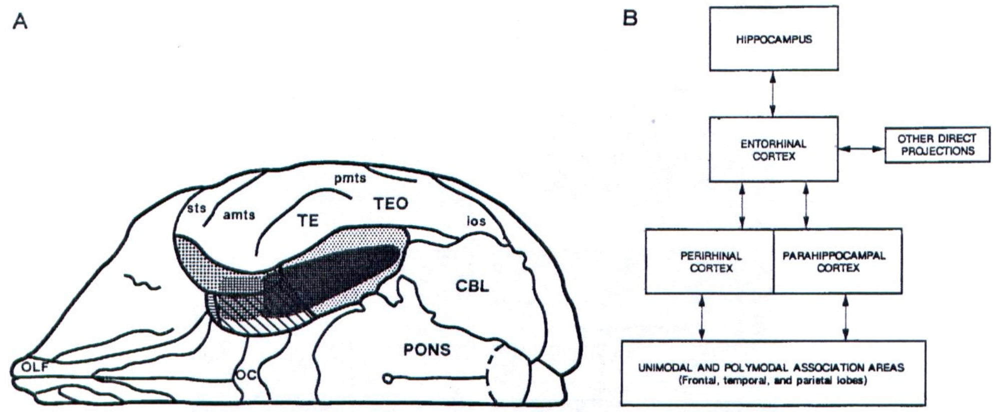


Fig 7-3 (a) H=hippocampus, A=amygdala, +=adjacent cortex underlying each structure, CBL=cerebellum, OLF=olfactory bulb, OC=optic chasm, sts=superior temporal sulcus, pmts=posterior middle temporal sulcus, ios=inferior occipital sulcus; (b) medial temporal lobe structures required for memory – entorhinal cortex is primary input to hippocampus, two-thirds of which orginate from perirhinal and parahippocampal cortices [from Squire 1992]

The hippocampus comprises a number of distinct regions – CA1-CA4, dentate gyrus, subicular complex and several cortical areas. There are two types of neurons in the CA3 and CA1 regions of the hippocampus – complex spike cells which are pyramidal low firing rate burst cells (place cells), and theta interneurons which have high spontaneous firing rates expressing rhythmic discharges (4-8 Hz). The hippocampus is the basis for declarative memory including memory for faces, facts, events, spatial geometry, etc. This is differentiated from procedural memory involved in perceptual-motor skills learning, habituation, sensitisation, simple conditioning and priming (increased facility for detecting familiar stimuli) which do not require conscious access to past episodes – these processes occur in the neostriatum and cerebellum. Procedural memory is specialised for incremental, cumulative changes over many exposures. The P300 event-related potential in the human brain with a latency of 300-700 ms is evoked in response to unexpected events and causes motor-event related hippocampal theta oscillation [Shin 2002]. Theta oscillations code motor commands and encode episodic memories of self-action within the hippocampus. The hippocampus has two orthogonal functions – the temporary maintenance of memories between short term and long term memory in the cortex, and the processing of particular types of classical conditioning memory in the brainstem and cerebellum [Eischenbaum et al 1994]. The hippocampus is required for learning object-place associations an conjunctions and spatial memory in general. The hippocampus contributes to the formation of new relationships such as in associating stimuli with their spatio-temporal or semantic contexts in single rather than repetitive trials. The hippocampus is implicated in memory storage until its establishment and consolidation in long term memory in the neocortex through the development of cortico-cortical connections within the neocortex. The entorhinal cortex projects directly into the hippocampus and receives 2/3 of its cortical input from the perirhinal and parahippocampal cortices. The amygdala is important in the acquisition of conditioned fear and affective significance of stimuli through emotional conditioning. Emotions are states generated by reward and punishment reinforcement. Cognitive maps in the rat brain reside in the hippocampus in the form of spatial representations of the environment. Spatial location is represented in the firing patterns of "place" cells, assemblages of which form the cognitive map. There are also head direction cells which act as internal compasses to orient the cognitive map. The hippocampus provides the integrative memory retrieval process that allows processing of perceptual information about objects that are no longer in view. There exist place cells in the hippocampus that fire at their maximum rate only when the animal is at a particular location relative to some external landmarks. Specific place cells in the rat hippocampus fire when the rat enters a local region of the environment (place field). Place cells are pyramidal cells that fire when an animal is in a particular location in its environment. Some are tuned broadly to a particular heading. They exhibit one-shot learning and respond to the identity, pose and spatial distribution of visible landmarks within a local sensory view. Similarly, hippocampal place cells respond to head direction. The hippocampus employs a relational strategy to encoding the environment. Displace cells respond to different combinations of place fields and body motions, between place fields, through place fields, etc. Theta rhythm is a large amplitude sinusoidal oscillations with a frequency of 4-12 Hz which occurs in the hippocampus during movement through locations relative to the environment [O'Keefe & Burgess 1999]. It is reckoned that the theta rhythm acts as a global synchronisation signal to phase lock other areas of the brain including other hippocampal regions and the brainstem reticular formation and the amygdala. Zipser's (1985) model of hippocampal place fields is based on input of the configuration of landmarks with the location of the observer. The output of the model represents place cell activity. Place cells compared stored representations of scenes with the current scene. The better the match, the closer the viewer to the stored viewpoint. A two layer network models this process – each neuron in the first layer is specific for one landmark and one place field compared to the current location parameter (eg. distance), firing maximally when the match is close; the second layer comprises a single place cell dependent on sum of its inputs from the first layer. There are three types of reference frame associated with biological place cell learning: allocentric (object-centred environment frame using landmarks or dead reckoning but limited by occlusions and drift), egocentric (viewer-centred frame defined with respect to organism's midline location and orientation) or semi-egocentric (organism-centred frame oriented with respect to the environment but are limited by drift). Hippocampal models may be metric or relational. In metric systems, a place cell might be associated with a cartesian coordinate with respect to a landmark, or place cell phase may code for egocentric direction to place field – they are prone to error accumulation. Relational models implement graph-like relations between place cells (activated by context) and propagate information through the graph by spreading activation from the goal to the current position. Self-organising maps implement topological navigation based on feature similarity. Diktiometric models associate spatio-temporal information with relations between places through associative learning. An object is characterised as a collection of characteristic views and transitions between these views. Stable object features – edges and corners – are extracted from the viewer-centred object image. This is transformed to a log-polar mapping for invariance to translation and scale. Location is coded as egocentric gaze direction according to internal body position measurements and external landmark coordinates in terms of azimuth and elevation. These are coarsely coded through two small arrays of overlapping Gaussian receptive fields encoding "what" and "where" respectively. This feeds an adaptive resonant theory (ART) neural network which clusters these views into aspect categories. Allowable transitions in terms of body motion trajectories are learned to move between place fields through contrast enhancement of sensory data within a recurrent neural network. Adaptive, hierarchical view-based, relational map-making system for navigating in a 3D environment defined by spatially distributed visual landmarks modelled on the rat hippocampus – MAVIN (mobile adaptive visual navigator) - has been developed by Bachelder & Waxman (1995). It encapsulates the neurocomputational architectures of "what" (object recognition) and "where" (location recognition) through conjunctions of landmark identity, pose and egocentric gaze direction with a neurocomputational architecture of "when" through conjunctions of learned places and robot motions. The separation of coding for shape and location allow redundancy to object/place coding insensitive to minor changes. The robot constructs a map of its environment from visual and motor inputs and assesses the effects of its motor activity. The "what" and "where" of landmarks are associated with "when" of motor action. The visual environment is self-organised into perceptual categories represented by viewer-centred patterns and these view patterns are associated with each other through reward reinforcement associations in terms of actions. This relational map-making involves learning adjacency relations between distinct places.

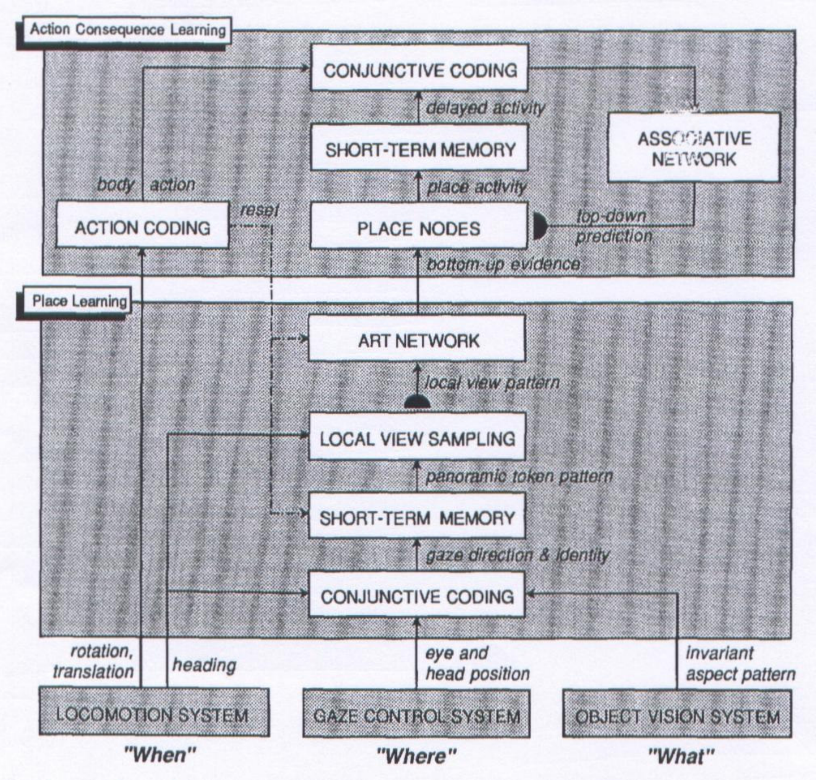


Fig 7-4 Place learning and recognition module and consequence learning module have inputs from object vision of landmark identity cues (what), gaze control system of eye-head position (where) and locomotion system of rotation, translation and heading (when)[from Bachelder & Waxman 1995]

Ordered connections are a characteristic feature of the organisation of the cortex which is arranged in sheets of microcolumns. Many of these ordered connections are topographic in that there is an ordered relationship between the peripheral receptors and the cortical area to which they project, ie. topographic maps of external space [Killackey et al 1995]. The primary somatosensory cortex is an isomorphic representation of the body surface. During embryonic development, such maps emerge sequentially from periphery through the thalamus to the cortical development. A similar process is repeated within the visual system whereby the development ocular dominance columns in postnatals is dependent on retinal activity for parcellation of the primary visual cortex. The mammalian auditory cortex is also organised tonotopically with distinct regions representing particular auditory frequencies. The representation of space is also linked with the motor cortex.

These techniques based on memorisation of cognitive maps have their primary utility in limited territoriality of animal behaviour. They thus have utility only in explorers which repetitively navigate in the same locality – this would be applicable in robotic support of human planetary bases but unlikely to be of much utility for robotic rovers designed for exploration range.

7.4. ONBOARD PLANNING & NAVIGATION

Higher animals such as mammals have behavioural patterns which are characterised by two types of behaviour: genetically inherited instinctive behaviours and learned behaviours. There are situations when the detection of a number of stimuli requires some internal processing such that the most appropriate behaviour or highest priority behaviour is selected according to the situation. Planning is essential for goal-aspiring, purposive behavior and this generally requires a world model. In the case of a Mars mission, the world is unknown a priori. Planning is typically divided into two realms – global path planning which generates a collision-free path towards the goal from the start point, and local path planning which generates detours from the global path around locally sensed obstacles. Global planning usually uses graph searching through free spaces in the environment. This requires the world to be modelled. An a priori world model must be updated with sensory data to compensate for a dynamic world. A world model M has the structure $<\theta, P, E, A, T, B, G, \varphi>$ where θ=a set of actions, P=set of other agents, E=set of primitive events, $A \in E \rightarrow P$=agent of events, $T \subseteq E$=set of possible events/worlds, $B \subseteq T \times P$=set of beliefs, $G \subseteq T \times P$=set of goals, φ=predicate interpreter. Indeed, McCarthy & Hayes (1969) considered that intelligence absolutely requires an adequate model of the world to enable the agent to perform tasks in the external world according to its goals and abilities and if necessary add information from the external world observed through the senses to the internal world model.

The problem of determining one's position in space is fundamental to navigation. Animals keep track of their position and heading whilst navigating through a known environment. Mature rats use non-geometric information such as odours and colours to navigate. However, whenencountering an unknown environment, they do not use such non-geometric cues. When a rat first explores an environment, it utilises allocentric representation of its own position with an egocentric representation for locating food and obstacles to form a cognitive map of its environment. In a familiar territory, it uses its memorised allocentric knowledge of its own and food source locations together with dead reckoning from environmental landmarks, ie. geometric cues. The key is the determination of its allocentric position prior to being able to navigate.

7.4.1. Artificial Intelligence as Search

The graph search uses a cost function in determining the energy consumption in following a given path. The most basic graph search method for finding the shortest route through the graph is Dijkstra' algorithm which maintains a working set of partial paths and updating the shortest distance at each node:

```
for all cell nodes v do dist(v): =∞  end for;
dist(S): =0;
Paths: ={[S]};
while Paths ≠ {} do
    select P from Paths;
    t: =head(P);
    for each neighbour n of t do
        newdist:=dist(t)+length(edge(n,t));
        if newdist < dist(n) then
            dist(n): =newdist;
             Paths: =Paths U {P+n};
        endif;
    endfor;
endwhile;
```

The algorithm allows the specification of breadth-first, depth-first or best-first searches. The best-first search expands the fewest paths but the depth-first search is the simplest while the breadth first search is a compromise. The Dijkstra algorithm is fine for theoretical purposes but is of limited value in mobile robotics. The "Find-path" problem requires the determination of a continuous path for an object from an initial location to a goal location while avoiding obstacles. The Configuration or C–space approach recasts the problem by keeping the robot away from obstacles which are modelled as convex polygons. Each convex polygon representing an obstacle is expanded to accommodate the dimensions of the robot into a C-space obstacle while the robot itself is shrunk to a point. An alternative method is the generalised cylinders approach which involves fitting 2D generalised cylinders to the space between obstacles which may be stacked in 3D. The obstacle-free space path between obstacles can then be computed. The shortest path should include rotations to avoid the expanded obstacles. This is done using the A* search algorithm which is the most-used search algorithm in mobile robotics. This graph-traversing best first A* algorithm can be used to find the minimum cost solution, ie. a minimax principle. It is a branch and bound graph search algorithm which uses the evaluation function to order nodes, combining lower bound remaining distance estimation with dynamic programming principles and is effective at dealing with average case situations though it fares less well under worst case scenarios. Minimaxing assigns one player a positive value and the other a negative value. Each node represents the state of the game. Values assigned to each node benefit either the maximiser or the minimiser. These search programs are similar to those used in games playing programs such as chess. Given any intermediate node N between the start node S and goal node G, the shortest straight-line path between N and G and from S to N can be computed. By expanding the most promising paths first, the optimal path for the minimum length between S and G:

```
for all nodes v do dist(v): =∞ end for;
dist(s): =0;
shortest: =∞;
Paths: ={[S]};
while Paths≠{} do
    select P from Paths with minimum minlength(P);
```

```
            t: =head(P);
            for each neighbour n of t do
                        newdist: =dist(t)+length(edge(n,t));
                        if newdist < dist(n) then
                                    dist(n): =newdist;
                                    Paths: =Paths U {P+n};
                        endif;
            endfor;
      endwhile;
```

The A* algorithm uses an evaluation function for ordering nodes. Path segments can be identified using the graph-traversing A* algorithm in constructing free space corridors representing straight-line trajectories between obstacles based on a distance-travelled cost function. The A* algorithm is an optimal path planning algorithm and requires a grid-based representation. It is imperative to use a metric thast minimises energy consumption and risk. Each arc segment has the following cost function [Morlans & Ligois 1993]:

$$C(A_i) = K_1 C_d(A_i) + K_2 C_n(A_i) + K_3 C_m(A_i)$$

where $C_d(A_i) = L.S_{\max}\left(\frac{1+\Delta z/L}{H(S_{\max}-\Delta z/L)}\right)$=distance and slope metric

$C_n(A_i) = \min(n_k)$ =ground characteristic metric

$C_m(A_i) = \left(\frac{(1/N)\sum_{i=1}^{N}\rho_v(P_i)}{H(\rho_0-\min(\rho_v(P_i))}\right)$ =mobility metric

Δz=height difference arc segment
L=length of segment
S_{max}=maximum slope
H(x)=0 if x<0
=1 else
A_i=A* segment
n_k=ground roughness
ρ_0=limit of curvature
N=pixel volume of segment

Straight line path segments may be found by a two step A* algorithm at coarse resolution, then finer resolution to generate safe paths – this two-step approach is computationally more tractable than a single A* search. If an obstacle is detected, a local path is derived around the obstacle back to its straight-line trajectory. Schiller (2000) introduced a metric for path planning based on the minimum time for traverse and vehicle stability. A three-stage optimisation process begun with determining the maximum speed along a path represented as a smooth cubic B-spline mesh between control points for which the vehicle is dynamically stable. The parameter optimisation and search for the best path proceeds normally.

A variant is Stentz's D* (dynamic A*) algorithm based on cell decomposition whereby each grid-based world model is built as local information gathered by the sensors [Stentz 1995, Stentz & Hubert 1995, Tompkins et al 2001]. The D* algorithm can plan paths in unknown or changing environments efficiently rather than re-planning from scratch. This is particularly suited to Mars exploration where the environment is unknown initially until sensory feedback is available. The algorithm uses sensory data to build a spatial grid of traverse data and plans paths that avoid obstacles while minimising the distance travelled. It provides planning with a reactive capability. The problem space is represented as a directed graph of robot state nodes connected by directional arcs representing costs. Every state except G has a backpointer b(X)=Y to the next state and the series of backpointers represents the path to the goal. The cost of traversing from state Y to X is c(X,Y). D* maintains an OPEN list of states to expand. D* initially computes the optimal path to all locations in the robot's environment. Similar to A*, it searches a map of traversibility cost values to find the least cost path to the goal. Initially, the goal state is placed on the OPEN list with an initial cost of 0. The state with the maximum path cost on the OPEN list is repeatedly expanded propagating path cost computations to its neighbours. If a new obstacle is detected, D* adds a very large value to the relevant cells and places the adjoining states on the OPEN list to propagate the path cost increases. As such RAISE states propagate, they meet neighbours that can lower their path costs which are then placed on the OPEN list. As the robot moves towards the goal, D* incrementally repairs the path on the basis of new sensory data. As cost values on the grid map are changed according to new data, D* re-computes the optimal path by "repairing" the plans incrementally. D* comprises of two functions – PROCESS-STATE and MODIFY-COST. Process-State computes the optimal path to the goal while Modify-Cost changes the cost of arc functions and enters effected states on the OPEN list. If a path from X to G exists, the algorithm will find the optimal path in a finite number of steps. The environment may be modelled as a 2D, 8-neighbour lattice with or without potential values and D* can assimilate C-space costs to allow for the finite extent of the robot and obstacles. It can accommodate fractal-like natural terrain. It is much faster than re-planning from scratch using A*. It is much more rapid than A* as the environment increases in size (up to 200 times faster). D* has been successfully implemented on a real-time autonomous HMMWV system [Stentz & Hebert 1995]. However, D* does suffer as does A* from the computational explosion characteristic of NP-hard problems as the search space grows. This is where heuristics could be useful – "behaviour" control could provide these heuristics. The major components of the D* algorithm are as follows [Stenz 1995]:

Function: PROCESS-STATE()

```
X=MIN-STATE( )
if X=NULL the return –1
$k_{old}$=GET-KMIN( )
DELETE(X)
#Reduce h(X) by lowest-cost neighbour if possible
for each neighbour Y of X:
  if $t(Y)$=CLOSED and $h(Y) \le k_{old}$.
    and $H(X) > h(Y)+c(Y,X)$ then
     $b(X)=Y$
     $h(X)=h(Y)+c(Y,X)$
  endif
endforeach
#Process each neighbour of X
for each neighbour Y of X:
  #Propagate cost to NEW state
  if $t(Y)$=NEW then
    $b(Y)=X$
    $h(Y)=h(X)+c(X,Y)$
    $p(Y)=h(Y)$
    INSERT(Y)
  endif
  else
    #Propagate cost change along backpointer
```

```
    if b(Y)=X and h(Y)≠h(X)+c(X,Y) then
      if t(Y)=OPEN then
        if h(Y)<p(Y) then p(Y)=h(Y)
        h(Y)=h(X)+c(X,Y)
      endif
      else
        p(Y)=h(Y)
        h(Y)=h(X)+c(X,Y)
      endelse
      INSERT(Y)
    endif
    else
      #Reduce cost of neighbour if possible
      if b(Y)≠X and h(Y)>h(X)+c(X,Y) then
        if p(X)≥h(X) then
          b(Y)=X
          if t(Y)=CLOSED then p(Y)=h(Y)
          h(Y)=h(X)+c(X,Y)
          INSERT(Y)
        endif
        else
          p(X)=h(X)
          INSERT(X)
        endelse
      else
        #Set up cost reduction by neighbour if possible
        if b(Y)≠X and h(X)>h(Y)+c(Y,X) and
          t(Y)=CLOSED and h(Y)>$k_{old}$ then
          p(Y)=h(Y)
          INSERT(Y)
        endif
      endelse
    endelse
  endelse
endforeach
#Return $k_{min}$.
return GET-KMIN
endfunction
```

Function: MODIFY-COST()

```
#Change the arc cost value
c(X,Y)=cval
#Insert state X on the OPEN list if it is closed
if t(X)=CLOSED then
  p(X)=h(X)
  INSERT(X)
endif
#Return $k_{min}$.
return GET-KMIN( )
```

L10 endfunction

Some problems in a world model may be reduced to more than one problem reduction operator resulting in alternative subproblems. This generates AND/OR tree inference nets where some goals are satisfied only when all the immediate subgoals are satisfied (conjunctive AND nodes) and other goals which require only one of several subgoals to be satisfied (disjunctive OR nodes). The branching factors should be as small as possible to keep the AND/OR tree manageable. Each node represents a set of possible world states and each action is a transition from a set of possible world states to a set of possible resultant world states. The solution to the planning problem should again lead to the goal in a finite time and minimise the maximum path length. The AND/OR approach was used by Sanderson, Peshkin & Homem De Mello (1988) to generate sequential plans for assembly/disassembly sequence tasks in satellite servicing such as those exemplified by the Solar Maximum Repair Mission. The AND/OR graph represents the assembly sequences with cost functions based on entropy measures. The assembly product was taken to comprise of several parts joined together in a stable configuration. This provides a natural representation of the hierarchical assembly process of pairs of parts and modular sub-assemblies [Nevins et al 1987]. A CAD database provided a geometric description of the assembly and its parts, their dynamic properties, geometric constraints, assembly relationships and parameters, and sensor-specific information. Such are needed to identify potential jigging and gripping surfaces, clearances and tolerances. Relational graphs were used to derive the relative positions and orientations of parts and subassemblies. The assembly planner used the geometric and physical constraints to derive feasible operational sequences of motion primitives using precedence requirements. The feasibility of sequences were based on contact and attachment relations according to a hierarchy of operational preconditions:
(i) release of attachments;
(ii) stability of subassemblies;
(iii) separability of subassemblies.
The AND/OR graph provides a natural representation of feasible assembly sequences. Each node of the AND/OR graph corresponded to a configuration subassembly which is connected by operations represented as a relational structure. Arcs corresponded to disassembly operations which if reversed provided the re-assembly sequence. The assembly/disassembly of the product was regarded as a backward path search using the AO* algorithm in the state space of all possible configurations of parts [Fu Gonzalez & Lee 1987]. The AO* algorithm is similar to the A* algorithm modified to handle the AND transition. AND nodes are best searched breadth first while OR nodes are best searched depth first. As the branching from the initial to the goal state (forward chaining) exceeded that from the goal to the initial state (backward chaining) a backward search was employed. Weights were assigned to arcs using criteria of operational complexity and subassembly degree of freedom to reduce the search space. Any task may be represented by:
Replace <part> *in* <product>
(i) *disassemble* <product> *until* <part> *is an independent substrate*
(ii) *replace* <old part> *with* <new part>
(iii) *reassemble* <product>
The assembly plan is input to the task planner which extends the assembly plan and produces a detailed task plan that describes detailed actions. The task plan comprises 3 phases: grasping which requires a list of grasp sites, collision-free trajectory generation, and fine motion strategy planning for insertion. An assembly world model provides a runtime description of the current state of the parts being assembled, ie. parts status and assembly completion status. The Solar Maximum Repair Mission involved the replacement of the main electronics box:

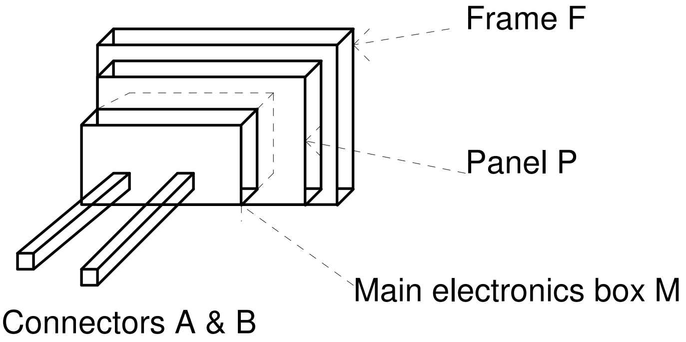
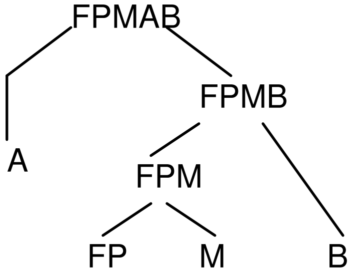


Fig 7-5 Solar Maximum Repair Mission Main Electronics Box Assembly (adapted from Sanderson Peshkin & Homem-De-Mello 1988)

The solution tree to disassemble the satellite is found by the path search:



In general, automated process/assembly planning reduces the lead time, increases consistency and more efficient production of the final product.

The domain-independent GPS (General Problem Solver) system represented the states of the world as logical assertions of first order predicate calculus. GPS used means end analysis as a domain-independent heuristic to compare the current initial world state (the problem) with the desired final world state (the solution) and then search for procedural operators that reduced that difference. GPS was the basis of STRIPS (STanford Research Institute Problem Solver) planner [Fikes, Hart & Nilsson 1972]. STRIPS has provided the basis for many subsequent planners and it has a central role in planning systems [Simon 1991]. Each action was an operator schemata which acted to change the state of the world towards the final goal state by describing the actions in terms of preconditions and effects. The sequence of actions selected thus comprised a search for the correct sequence of actions to achieve the goal. The operator was characterised by an ADD-list which listed the consequent changes to add to the world model by the application of the operator, a DELETE-list which listed antecedent deletions to the world model by the application of the operator, and a PRECONDITION that provided the context of logical formulae to be fulfilled so that the operator may be applied. The ADD and DELETE list effectively described the assertions that would be true after execution, ie. the effects. These properties of each operator localised the effects of each operator. Plans were built from these operator schemata in an ordered sequence through the search space of intermediate states from the initial to the final goal state by transforming the world model from one intermediate state to another. The operators were essentially sets of condition-action propositions like production rules. The conditions defined the circumstances that must exist before the operator may be fired. The actions define the effects on the world and the body of the rule describes the decomposition of actions into subactions. The plan was a tree of nodes representing a hierarchy of actions and their temporal order down to the level of primitives. The chief problem of STRIPS and all its variants is that they are capable of dealing with only simple planning problems. Problems such as the Tower of Hanoi problem which

require overcoming obstacles to goal reduction are not soluble by these methods based on reducing searches. The Towers of Hanoi problem comprises of 3 pegs and a set of different sized disks stacked on one of the pegs in decreasing order of size. The problem is to transfer all the disks from one peg to another with the constraints that:
(i) one disk is moved at a time;
(ii) the larger disk cannot be placed onto a smaller disk.

The environment is constantly changing and reasoning in the real world must reflect this. STRIPS and similar planning programs suffer from the "frame" problem which arises out of the dynamic nature of the world [Hayes 1973]. In the process of planning, each action changes certain specific features of the situation. The frame problem arises from the need to represent those aspects of the world which remain invariant during state changes. The difficulty is in keeping track of the consequences of performing actions and the required alteration to the world model representation in real time. Since successive states of the world are logically independent, the difficulty is in deciding which statements continue to be true and persist after the performance of a given action. Indeed, generally almost all the assertions will continue to be true after the action has been applied as most of the world is unaffected by events as they tend to make only localised changes to the world. It is necessary to state that actions change only features of the situation to which it directly refers. STRIPS localises the effect of actions so that almost all the statements continue to be true to the next state unchanged unless explicitly eliminated. One possibility is to include "always true" frame axioms to explicitly represent the invariants but this limits flexibility and nullifies the inherent logical correctness of the planning process. Furthermore, the number of such frame axioms becomes very large if the world model is complex. SHRDLU was a planning program similar to STRIPS designed to demonstrate natural language communication which operated in a limited "blocks" microworld of simple 3D objects such as cubes and pyramids on a flat surface in an attempt to tackle the problem of context [Winograd 1980]. The simulated microworld was limited however. The blocks world was characterised only by geometric shapes and dimensions. The real world is far more complex, uncertain and dynamic than the blocks microworld.

Another important problem is that of the conjunction of interacting subgoals whereby if any one of the subproblems is solved independently, the solutions to others may be destroyed [Chapman 1987]. Some goals are conjunctive goals which satisfy several constraints simultaneously. The traditional strategy for achieving goals P and Q is to first derive a solution to achieve P first then modify it to achieve Q also. But this will not necessarily work as actions can have side effects (variant on the “frame problem”). Such goal interactions are ubiquitous in planning. One strategy for dealing with this is to reach subgoals independently and then treat interactions as they arise. This method is inefficient when many subobjectives occur. Planning may be linear whereby the sequence is totally ordered or nonlinear whereby the sequence is partially ordered. This method of partially ordered nonlinear planning reduces the necessity for backtracking and allows concurrent actions to be performed in parallel, eg. NOAH which was the first nonlinear planner that used partial ordering on subgoals until execution time at which point the complete plan with total ordering must be decided – this approach was characterised by several later planners. The NOAH system saved the state of the solution at each point where there were alternative actions and kept a record of alternative choices. Many planners work entirely in block worlds, eg. HACKER, NOAH and even reach a high degree of sophistication, eg. BUILD. Allen & Litman (1986) advocated the use of metaplans, ie. sets of plans about the planning process itself independently of the domain itself. The metaplan defines constraints such as resource limitations and the contexts of applicability of plans. Metaplans include the plan as a knowledge domain in itself, information concerning the introduction of plans, the execution of plans, the abandoning of plans, etc. independent of the plan domain. Such metaplanning allows the planner to reason not only about the goal but also about the various techniques available for plan generation. Goals (metaplans) are given priorities with the highest priority goals being considered first. Metaknowledge (knowledge about knowledge) may be implemented independently of object level knowledge. Metaknowledge in the form of metarules to guide and constrain searches of knowledge bases of object level statements make effective use of heuristics. Chunks of metaknowledge may be embedded into the object level knowledge as objects using the object level rules to communicate between the metalevel objects (object level programming). The metalevel representation can devise proof strategies, control inferencing and increase the expressive power of knowledge and implement control knowledge (heuristics). Metaknowledge increases the power of inferencing and reduces the length of object level proofs. This allows the procedural use of declarative knowledge. Metaknowledge provides the means for chunking object level sequences into metalevel objects which do not need to be recomputed as a limited form of learning. Weybrauch (1980) described FOL (first order logic) as an expert system whose expertise was reasoning, ie. a meta-reasoning system.

As the world changes over time, it is necessary for the planning system to represent time. Time is a major problem for planning systems that regard the world's evolution as a sequence of states with actions causing state changes in the world. A plan is essentially a representation of some aspects of the future. Most actions take time and several can occur at once. Time specifies when conditions should be achieved and for how long they should be maintained. However, many temporal constraints are imprecise due to their relative nature, a lack of a clear relationship between temporal markers and different temporal scales. Planning of activities occurs in a temporal universe with deadlines and external events. Each activity is defined by a temporal window with a start time and a duration. Since much temporal knowledge is relative rather than involving absolute dates and times represented by temporal coordinates, Allen & Litman (1986) introduced a temporal logic based on the temporal interval to accommodate inexact relationships between intervals through a disjunction of primitive ordering relations such as X<Y (X before Y), Y>X (Y after X), X=Y (X concurrent with Y), and XoY (X overlaps Y). This allows the formation of a constraint network comprising directed acyclic graphs of nodes representing interval connected by arcs which relate the intervals. DEVISER is a 4000 line INTERLISP planner designed for Voyager spacecraft mission sequencing (though adaptable to different missions) which adopted a sophisticated notion of time to generate partially ordered plans and it was based strongly on NOAH [Vere 1983]. It generates parallel plans to achieve goals with time constraints imposed. Similar to STRIPS, it implemented productions with pre-conditions, a delete-list and an add-list. It generated plans by backward chaining from unordered subgoals. Conflicts are resolved by ordering formerly unordered plans. For instance, subgoals which were parallel may be resolved sequentially. The syntax may be given by (believe A S I) which means that agent A believes sentence S to be true during the time interval I. Actions occur during intervals and these intervals are ordered. Every perception of the environment, every internal inference and every command to the actuators is given a time stamp. Typically, windows provide an upper and lower time bound for activities. They may be explicitly specified or computed dynamically during plan generation for scheduling. DEVISER simplifies the process of conflict resolution. The default window is the “anytime” window with an eternal duration. A variant on DEVISER is Spaceworld which provides an environment for which an autonomous spacecraft such as Voyager can schedule photographing objects in deep space and transmitting the information to Earth. DEVISER simplifies the process of conflict resolution. MARVEL (multimission automation for real-time verification of spacecraft engineering link) has been used on Voyager since 1989 to monitore spacecraft telemetry to detect departures from expected behaviour to reduce operator workload.

7.4.2. Artificial Intelligence as Knowledge

Planning viewed as a search problem suffers from certain problems. The search space can become large and grow exponentially and searching for a path can involve exponential computation. Furthermore, finding an optimal plan in even a simple blocks world is an NP hard problem and so fundamentally intractable due to the conditional dependency of effects of actions on the input situations and the frame problem of discovering which propositions are unchanged by an action and derived side effects. When search trees become large, the computational cost of solution may become impractically large. One way to direct the search pattern in promising directions is by using informal heuristics to constrain the search and increase the search efficiency. These heuristics are vague truisms and are used to generate weak forms of implication "if p then q". This shift represents the Knowledge Principle whereby search and reasoning alone is regarded as insufficient for intelligent behaviour - a great deal of knowledge of the world in which the agent operates is required [Lenat & Feigenbaum 1991]. Knowledge is one of the prerequisites for intelligent behaviour and in effect represents the agent's learning history. Much of this knowledge should be sufficiently general to enable its use for multiple but specific domains (the Breadth Principle). Such knowledge imposes descriptions of regularities in the world including declarative maps, planning constraints, etc. Human thought is a pragmatic device based on factual content rather than logical syllogism, ie. it is knowledge-driven. Mental models are context-dependent with conceptual knowledge forming the central utility in high level cognition. This is model-based reasoning which draws heavily on world knowledge rather than logical inferencing and assumes that the mental models correspond to the real world. Systems composed of a few inference rules but with a lot of declarative knowledge present a very powerful process due to the large combinatorial number of ways facts can be combined using those rules. This knowledge-based approach to problem solving encodes programs that describe real world relationships through constraints and rules to provide solutions by outlining sequences of actions while utilising a reasonable expenditure of resources. The artificial intelligence paradigm is based on storing knowledge as a set of symbols which are manipulated according to a set of formal algorithmic rules – it is based on the assumption that all knowledge can be so formalised, ie. automated logical reasoning [Simon 1978, Post & Sage 1990]. Plan generation has been traditionally viewed as the generalisation of the programming language process in that the plan represents a possible solution to a problem through the execution of an effective well-defined procedure, ie. planning is an algorithmic problem solving process. The purpose of planning is to generate a sequence of actions to achieve given objectives and goals. Ultimately, plan generation may be regarded as a form of self-programming and this is a major goal in robotics to develop autonomous capabilities to machines.

Expert systems are programs that solve problems normally requiring the knowledge and skills of human experts [Hayes-Roth 1984, 1985a, b, Hayes-Roth & Jacobstein 1994, Klisker 1986]. Essentially, they model human decision making processes through the use of knowledge bases. The knowledge base acts as the agent's model of the world albeit incomplete. The knowledge base loosely represents stable long term memory (LTM) and they are limited to specific problem domains. Real world data in a dynamic global working memory database (loosely correlating to short term memory (STM)) must be matched against knowledge stored in the knowledge base. Events comprise the inputs to the working memory which is acted upon by an inference engine. The inference engine is independent of the knowledge base and emulates deductive behaviour through logical procedures for searching and deriving conclusions from the sets of facts in working memory. The inference engine interprets the current state of working memory and applies the relevant logic procedures which specify the changes to be made. Production rules for state representation are particularly suitable for use in robot planning and are the commonest form of logic representation. A production system consists of a knowledge base containing all the task relevant information in the form of a set of production rules. Production rules represent relatively independent chunks of knowledge and are used by the inference engine to infer solutions to problems. Production rules define relationships between the rule's terms through implication. These rules consist of one or more antecedent precondition statements linked to one or more consequent action statements (condition-action rules). They essentially model plausible hypothesis-conclusion inferencing logic for problem solving through deduction. They can be used to model routines with particular input-output characteristics compactly as stimulus-response behaviours. Clauses may be combined using Boolean logic operators. The rules may be represented as: if <condition P_1...P_n> then <action Q_1....Q_m>. The condition is usually the conjunction of a number of predicates while the action is usually single predicate. They provide a means for making hypothetical statements about the world. They incorporate practical conditional if-then knowledge and can solve reasonably complex problems by combining the rules into sequences and indicate explicit lines of reasoning. The precondition statements determine the applicability of the rules in terms of the conditions that must be true for implementation of the rule. The action statements are the operators which determine the effects of the action if the rule is applied to the world model.

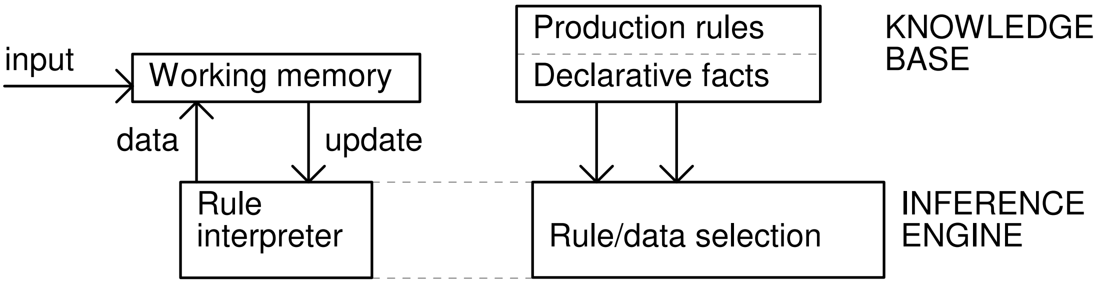


Fig 7-6 Knowledge-based expert system

Applications of expert systems are multitudinous: for medical diagnosis of bacterial infection (MYCIN), mineral prospecting (PROSPECTOR), electronic component troubleshooting (ACE) or organic molecular analysis (DENDRAL). Other successful implementations of rule based expert systems include the DARPA (Defense Advanced Research Projects Agency) ALV (Autonomous Land Vehicle) which is as autonomous mobile vehicle for battlefield operations. NAVEX is an expert system for the interpretation of space navigation data. Drabble (1991) advocated AI techniques for spacecraft control and automation of mission operations using knowledge based planning by expert systems. The spacecraft itself and the environment in which it operates are comparatively well structured (no unpredictable free agents around, ie. people) so it is well suited to automation to reduce the human workload of spacecraft monitoring. Indeed, AI techniques have been used for the automation of fault isolation and diagnosis on the Space Shuttle thruster reaction control system [Georgeff & Lansky 1986].

There are two main forms of knowledge representation commonly used in expert systems, frames and production rules, of which the latter are the most popular [Nau 1983]. Frames are schematic, modular data structures for representing generic concepts concerning objects, classes of objects and situations. Frames provide a natural representation for declarative knowledge (knowledge about something) while production rules are usually used for procedural knowledge (knowledge about how to do something) [Fikes & Kehlar 1985]. Frames and production rules may be integrated into a hybrid representation scheme so that frames can represent procedural action oriented knowledge. Production rules can be attached to frame slots as values to be invoked as demons when the frame is invoked. This ability to attach rules or rule classes as demons to frame slots provides great flexibility in controlling reasoning particularly for reactive functions. Conceptual dependency structures can be built with groups of production rules appearing in different concepts. Indeed, this type of representation has been under development as an intelligent aid to human satellite operators in the expert diagnosis and correction of satellite malfunctions (STAR-PLAN).

Nomad is an Antarctic rover that implements rudimentary scientific decision-making capability in its search for meteorites [Apostolopoulos et al 2001]. A Bayes network is used for classifying sensory data according to prior expert knowledge held in the scientific knowledge base. Bayes networks are graphical models of statistical relationships between feature sets and data sets. Bayes theorem computes the posterior probability of hypotheses based on evidence and prior knowledge optimally. Belief networks represent causal relationships and allow the integration of logical inferencing with Bayesian probability. Belief networks are directed acyclic graphs with nodes in the network representing probabilistic sensory data selected by joint probability distributions. Evidence comprises the state of the nodes in the network which is propagated through the network through bi-directional links giving an overall joint probability distribution. NASA's Multi-Rover Integrated Science Understanding System (MISUS) is a planning/sceduling system with machine learning capabilities. It can classify different rock types using clustering methods to group rock types into classes by analysing multi-spectral images. The planning/scheduling component determine rover activities to maximise the quality of scientific return. The multi-rover integrated science understanding system (MISUS) combines planning with machine learning for autonomous scientific exploration onboard planetary rovers [Estlin et al 1999]. Science data is generated from machine learning clustering methods based on image and spectral mineralogical features to classify different rock types. The unsupervised clustering methods search based on mixture of Gaussian functions for similarity classes of spectral images of rock. Output clusters are used to evaluate scientific hypotheses and prioritorise regions for further analysis. As the system builds models of the rock type distribution, it assembles new observation goals which are passed to the rover planner (ASPEN).

Traditional approaches to spacecraft commanding involves uploading a detailed sequence of time-tagged commands for each device onboard, but such sequences are prone to failure if the situation changes. Autonomy is essential to make good unexpected science opportunities, reduce reliance on the ground station and dealing with uncertainties and faults with high reliability. The US Deep Space 1 (DS 1) launched in 1998 to flyby asteroids and comets implemented an AI-based control architecture for just one week comprising of a planner, plan executor and model-based fault diagnosis and reconfiguration system [Pell et al 1998a,b; Pell et al 1997]. AutoNav was the autonomous optical navigation system. It used a onboard stored catalogue of the position of 250,000 stars from the Tycho catalogue. AutoNav acquired optical navigation images from a star tracker to compute its position and commond onboard thruster operations for attitude control. The MICAS (Miniature Integrated Camera/Spectrometer) was a 12 kg derivative of the Pluto Integrated Camera/Spectrometer stated for the Pluto-Kuiper Express. It included two panchromatic visible imaging channels with a 1024x1024 pixel CCD and a 256x256 CMOS pixel sensor, an ultraviolet imaging spectrometer and an infrared imaging spectrometer, all sharing a single 10 cm diameter telescope. AutoNav communicated with the ground only bi-weekly but failed once the star tracker failed and new software had to be uploaded. DS1 also carried the combined 5.6 kg/9.6 W PEPE (Plasma Experiment for Planetary Exploration) which can electronically measure ion and electron plasma energy distribution from 8 eV to 33 keV over its 2.8π sr FOV.

Another approach to high level/low level control interfacing was based on automata theory in the form of DEVS (discrete event systems specification) as an intelligent control logic [Zeigler 1989]. It is event-based in that the controller expects confirming sensor responses to control commands and provides a means to interface continuous control with symbolic reasoning systems. The controller sends out commands and samples the sensors at regular intervals for control purposes. Returned sample values are tested on the basis of which corrective control actions are commanded. The controller expects to receive confirmatory sensor responses to the control commands within definite time windows. State changes only occur at event times between the window durations. The narrower the time window, the better the error detection. High hierarchical planning levels determine the sequence of actions in symbolic form. Event-based logic provides the means for scheduling sequences of actions, expected responses, and response time windows. An interpreter of the schedule sends out commands to the low level servo-controller and takes the appropriate action to the expected responses. The event-based controller generates error messages for diagnostics by the high level planner to rectify faults and return to normal operations. This provides the basis for a robot cognition model that functions by action-through-error. The plan specifies a sequence of operations to transform the process from the initial to desired states. Each operational segment has a time window for completion and each such transition is scheduled sequentially according to the trajectory of the dynamic model.

Remote Agent was an expert system of encoded rules used to plan the spacecraft's maneouvres according to high level goals. It integrated planning and scheduling with real-time monitoring and control and model-based diagnosis and reconfiguration. Remote Agent took 4h to produce a three-day operations plan on a 25 MHz RAD6000 onboard processor utilising 25% of CPU time. The planner/scheduler expanded the goals into a plan which satisfied constraints on resources available. The detailed sequence of commands to achieve the goals is generated onboard DS1 by the planner. The plan is a set of timelines comprising of linear sequences of activities defined by their temporal windows. There are three different types of constraint: before, after and meets. Before constraints define pre-conditions, after constraints define post-conditions (similar tro STRIPS) while a "meets" constraint defines coincident activities. The execution of activities are defined by the following algorithm [Pell et al 1997]:
(i) wait for the beginning of the activity's start window;
(ii) in parallel: (a) wait for the activity's pre-condition to be true;
 (b) check that the end of the start window has not passed; if so, flag failure;
(iii) flag the start of the activity;
(iv) execute the activity;
(v) maintain the activity as a parallel task;
(vi) wait for the start of the activity's end window;
(vii) wait for the activity's post-conditions to be true;
(viii) wait for the pre-conditions of the next activity to be true;
(ix) stop activity maintenance of the activity;
(x) check that the end of the end window has not passed; if so, flag failure, else flag activity end.

The plan is carried out by the executor. If deviations from the plan occur during execution, the fault diagnosis and reconfiguration engine attempts to repair the plan rapidly within the constraints of the situation. The planner scheduler is the deliberative layer while the executor in conjunction with the fault diagnosis and reconfiguration engine is the reactive layer. The executor carries out the planned sequence of activities while monitored by the fault diagnosis and reconfiguration engine. The cost of generating the plan is high in terms of computation and grows exponentially with the number of goals to be achieved. In the event of plan failure, the executive enters a stable standby state.

The plan comprises of a linear, temporal sequence of activities, each of which has an earliest/latest start time and earliest/latest end time. The planner minimises its commitment to provide robustness by retaining the flexibility of earlest/latest start and end times. Pre- and post-constraints describe dependencies of each activity, both sequential and parallel. Remote Agent adopted a hierarchical decomposition scheme to generate plans through subgoaling. Procedures in the plan can be sequential and/or parallel. The time window for each activity provides flexibility for repairing plans by the executor. Constraints include synchronisation requirements, safety restrictions, and resource conflicts. Compatibility constraints coordinate behaviours across different activities on different timelines. Resources include sources of electric power for which there are competing requirements. Knowledge for the planner is distributed among domain modules and the planning experts. The domain models enable behavioural constraints on the spacecraft. The planning experts are software modules which encode specialist subsystem knowledge [Smith et al 1997].

Waypoints are included iteratively in the plan as boundary checkpoints for scheduling. The planner searches through partial plans using its temporal reasoning capabilities to build it into a complete plan [Muscettola et al 1997, 1998]. Temporal information is represented as temporal constraint networks. The commonest conflict is resource over-subscription and such conflicts are resolved according to primitives. Goal achievements can be postponed to provide flexibility in the execution of the plan so if a plan becomes useless, replanning is undertaken to generate a new plan with re-assessed goal. Reactions to contingencies include retrying failed actions, reconfiguring of spacecraft subsystems or entering safe modes to prevent damage. Due to the limited sensor suite on a spacecraft, there is limited observability of the spacecraft. This imposes the need for sophisticated model-based diagnostics. Furthermore, sensors are subject to hardware failure. The fault diagnosis and reconfiguration engine models onboard devices as qualititative models to predict their behavior rapidly. Rules are included which encode device states and diagnostic fault identification. Safe mode is an operating mode which activate a minimum number of hardware components. The fault diagnosis and reconfiguration engine used a directed best-first search to find the device states most consistent with observations. Recovery actions push back the end time of an activity and adjust the start times of subsequent tokens accordingly [Bernard et al 1998].

In Remote Agent, emphasis is placed continuous iterative repair of plans to robustify their utility and reduce the amount of re-planning required – CASPER (Continuous Activity Scheduling Planning Execution & Replanning) provides greater responsivity to unexpected circumstances. It employs a satisficing approach to maintain consistency rather than optimality. Rather than implementing a batch process which is based on an initial state and a goal state, the continuous planner CASPER maintains a current state, current goal and current plan. The plan must incrementally be updated as time progresses and can replan if conflicts arise, failures occur or parameter updates occur [Chien et al 1999]. The basic algorithm is as follows:

```
Initialise P to the null plan
Initialise G to the null goal state
Initialise S to the current state
Given current plan P and current goal G
    (i)     update G to reflect new goals and delete goals no longer required
    (ii)    update S to the new current state
    (iii)   compute conflicts on (P, G, S)
    (iv)    apply conflict resolution planning to P within resource bounds
    (v)     release relevant near-term activities in P to Executor for execution
    (vi)    goto 1
```

One implementation of this approach that has been developed is ASPEN (Automated Scheduling & Planning Environment). It is a modular, reconfigurable set of re-usable software components that implement functions common in planning/scheduling systems based on temporal reasoning for resource management particularly suited to planetary rover applications which requires continuous reactive capabilities. All resources on a spacecraft or planetary rover are highly limited and subject to hardware faults. It automatically translates high level goals into a valid sequence of low-level commands within resource constraints. It uses an internal spacecraft model and can repair plans by propagating changes to the plan and resolving conflicts continuously. Chien et al (1999a,b) decsribe a 80h autonomous drilling expert system originally designed for the cancelled US Deep Space 4/Champollion comet lander. It used high level commands such as STEP, FFWD, MOVE-DRILL, START-DRILL, STOP-DRILL, TAKE-PICTURE, TURN-ON <device>, etc. The planner modelled 11 resource operations including: drill location, battery power, data buffer and camera state, and 19 activities such as uplink data, move drill, compress data, take image, and perform oven experiment. There were 3 major classes of activity: drilling and material transport to surface, instrument activity including imaging and in-situ materials experiment, and data uplink of which drilling is the most complex. There were 3 separate drilling activities. Each drilling activity drills a separate hole and acquires samples at three different depths during the process at the surface, at 20 cm depth and at 1m depth. Acquiring samples involves 5 separate mining operations after the holes have been drilled to remove 1 cm of material.

7.5. NEURAL & GENETIC APPROACHES TO CONTROL

Soft computing techniques are characterised by learning capability and learning is one of the most fundamental components of animal behaviour. Pavlovian (classical) conditioning reinforces the stimulus to force a response while Skinnerian (operant) conditioning reinforces the response by issuing rewards/punishment. Learning is fundamentally based on inductive inference in reasoning from the particular to the general. All biological organisms must adapt to their environments in order to survive. The most basic form of learning in complex animals is classical (Pavlovian) conditioning which comprises repeatedly presenting an animal (dog) an unconditioned stimulus (bell) with a conditioned stimulus (food) that triggers a conditioned response (salivation). This builds an association between the unconditioned stimulus alone (bell) and the unconditioned response (salivation). This type of learning is open loop. Instrumental (Skinnerian) conditioning involves an animal performing an arbitrary action (press a lever) in the presence of another arbitrary event (light flash). When the appropriate action is delivered, it receives a reward (food), otherwise it receives nothing or a punishment (electric shock). This type of leaning requires feedback (reinforcement). Associative learning of appetitive food-predicting stimuli – odours as reward-predictive stimuli which evoke proboscis-extension response - forms part of foraging behaviour in honeybees [Hammer 1997].

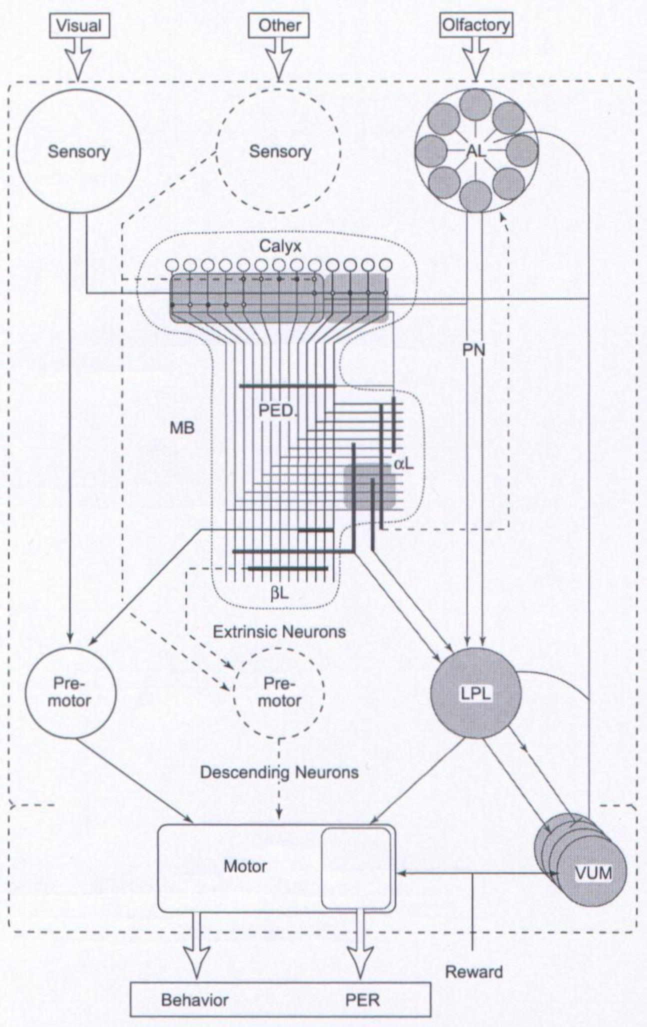


Fig 7-8 Model of functional organisation of bee brain underlying learning, memory and experience-dependent control of behaviour [from Hammer 1997]

Sucrose reward represents the US in olfactory conditioning in honeybees where the proboscis-extension response develops at CR in response to odour (CS). The odour must shortly precede but not follow the reward during learning. During foraging, several floral characteristics such as location, shape, colour and pattern symmetry can also associated with rewards. A single neuron, the octopamergic VUMmx1 neuron which responds to sucrose with long-lasting excitation is responsible for olfactory conditioning within the mushroom bodies. Artificial neural networks are ideally suited to implementing adaptive, learning robot controllers for navigation including obstacle avoidance, taxes landmark recognition and cognitive maps. The DRAMA (dynamical recurrent associative memory architecture) neural network design offers learning time series data with computationally inexpensive learning [Billard 2000]. Each connection is characterised by two parameters – weight and time – both of which are updated during learning. Weight codify activation frequency while time codifies activity decay.

Activation function is given by:

$$y_i(t) = f\left(x_i(t) + \tau_{ii} y_i(t-1) + \sum_{j \neq i} (1 - \theta(| y_j(t-1) - \tau_{ji} | \varepsilon(\tau_{ij}))(\theta(w_{ji}, \delta(w_{ji}))) \right)$$

where f(x)=x for x≤1
=1 otherwise
τ=time constant of membrane
w=connection weight
θ=threshold function=1 when x≥H
=0 otherwise
ε=error margin in time (time delay)
δ=weight threshold= $\frac{\max_{y_j > 0}(w_{ji})}{\theta(w_{ij})}$

The training rules are given by:

$$w_{ji}(t) = w_{ji}(t-1) + a$$

$$\tau_{ji}(t) = \frac{\tau_{ji}(t-1)(w_{ji}/a) + (y_j(t)/y_i(t))}{(w_{ji}/a)+1}$$

Low level control can be achieved using nervous nets which are being applied to "satbots" of dimensions <10cm and masses <100g [Tilden 1995]. This is the BEAM (biology, electronics, aesthetics and mechanics) robotics approach. Nervous nets are similar to biological control pattern generators. Neurons comprise of a capacitor, resistor and Schmitt inverter with the input capacitor and resistor tied to ground. Nervous nets represent non-linear analogue control systems where arrays of sequential RC time-based pulse circuits are aranged in closed loops. The time for signal propagation in the resultant delay circuit is given by t=RC where C=0.7-1.0μF and R=1-5MΩ. The initial resting state is a low input with a high output. The low-to-high transition at the input causes the output to remain low until the capacitor charges through the resistor. Once the capacitor is charged, the output switches to high. The hysteresis of the Schmitt trigger eliminates transients when the input is in the linear region. The most common kind of nervous net is the micro-core which comprises of 4 or more neurons in a loop. When a pulse is input to the inverter, the initially charged capacitor discharges. The capacitor then begins to charge through the resistor generating a potential at the input of the next inverter in sequence. However, the Schmitt trigger at the next input will not output a signal until the inverter input potential reaches a threshold. This provides the sequencing delay. If the loop is powering a sequence of motors, the pulse travels around the loop causing each motor to go low one at a time producing an out-of-phase dynamic in the motors. Such pulsed delay circuits can be used to control the legs of a robot or any other set of appendages.

Kuperstein et al (1987) have applied artificial neural networks to robotic control by providing a means for adaptive visual-motor coordination. This involves the process of mapping directly between a sensory input and a motor output through a topological map stored in the connection weights of the network. A neural network was used to adaptively control a visually guided robot manipulator arm using pattern recognition. It essentially learned an adaptive camera-position topographic model of the environment from an egocentric frame of reference based on sensory-motor reactions over a sequence of trials of different movements. The manipulator was controlled using consistency between the signals used to drive it and the signals received on sensing the results of the movement. The robot learned to correlate visual end effector positions from stereo cameras with joint motor activity signals producing those end effector positions, ie. joint angle to end effector position mappings. This provided visually guided behaviours.

Although artificial neural networks have been applied to adaptive robot control in various guises, they have yet to be applied extensively in space systems. The lack of verifiability and validation of neural network control behaviour makes their use somewhat controversial from a reliability point of view. Generally, space-rated software are validated as algorithms but the world of control systems is inherently heuristic, fuzzy and uncertain. In their favour, neural networks often provide robust control strategies in the face of such uncertainty and may certainly be used if more conventional techniques were used for backup. Their chief disadvantages are the need for lengthy training periods and the necessity for re-training from scratch when system parameters change. Furthermore, neural network configurations such as number of layers, number of nodes per layer and connectivity cannot be selected systematically. It is unlikely that they will be used in the near future for space robotic applications.

Dorigo (1993) implemented behaviour based control methods using genetic algorithms (GA). The GA's provided a mechanism for reinforcement learning based on the performance of robotic behaviour and generate feedback concerning the success or failure of actions. The genetic algorithms were implemented as classifier systems in the form of condition-action rules constructed from "chromosomes" based on symbol strings of the form: if <sensor data> and <current goal> then <action> formed from a three-valued alphabet A=(0,1,*). The classifier rule is composed of a number of chromosomes which represent the condition-action information as a string of three chromosomes. The first two chromosomes comprised the condition part while the third is the action part. The classifier may send messages to the effectors directly or to other classifiers. A set of such rules comprises the knowledge base and new rules may be generated from past experience. A message list collects all the messages to and from the environment via an input-output interface of detectors and effectors. Environmental messages in the message list are matched against the condition parts of the classifier rules and those that match are activated in parallel. A feedback mechanism provides reinforcement learning via reward/punishment. An apportionment of credit algorithm distributes the payoff to the rules that performed the actions. The GA provides a means for rule discovery through modification of the population of solutions. A fitness function relates rule solutions to performance. The value of this fitness function is determined by the rules' usefulness as calculated by the apportionment of credit algorithm. The worst classifiers are replaced by m new classifiers. In this way, an internal world model is built up corresponding to factors in the external environment. The apportionment of credit algorithm classifies rules according to their usefulness (determined by the fitness function). A variable real valued strength is associated to each classifier. When a classifier invokes an action on the environment a payoff is generated the value of which depends on the effectiveness of the action. For multiple and sequential rules, the bucket brigade algorithm passes reward back through the decision chains so that the payoff flows backwards. The system may be implemented as several classifier subsystems acting in parallel where each classifier subsystem learns a simple behaviour (such as avoidance of obstacles, grasping of objects, etc) through interaction with the environment. Sensors monitor the environment while rules determine which actions are to be taken. The system as a whole learns to coordinate its activities at a higher hierarchical level. As hierarchical structures learn faster than single level distributed architectures, an hierarchical structure of behaviours is produced. The hierarchical structure has the lowest level classifier system learning basic behaviours from sensory data while those at a higher level learning to coordinate those behaviours with no direct access to the environment. Such coordination learning leads to more complex behavioural sequences. Each classifier system receives excitatory and inhibitory signals from the classifier systems connected to it. Classifiers at the same level compete. This enables the system to distribute behavioural knowledge across the architecture. The experimental unit was successful at following lights and avoiding heat sources. The coordination level learned a switching procedures between the two low level behaviours. Essentially it may be regarded as a coarsely structured neural network. Indeed, it may be that the higher level coordinating behaviours could have subsequently evolved symbolic reasoning capable of manipulating the classifier rules as a superstructure built onto the instinctive behavioural base. This approach was extended and applied to a small robot AutonoMouse which had two eyes. Each classifier system of 100-500 rules was implemented on a distributed set of transputers as its brain, each with a specific behaviour arranged hierarchically (Alecsys) [Dorigo 1995]. It successfully exhibited simple light following, evasion of sounds, homing, and coordination of switching between these simple behaviours.

Koza (1993) applied the technique of genetic programming for the control of autonomous mobile robots. Genetic programs operate on the level of symbolic expressions. A computer program comprises of a set of functions (eg. logical operations). The computer program represents the solution to a problem. A population of computer programs comprises a generation. The initial population of computer programs is random. Each program is executed and assigned a fitness value according to how well it solves the problem. New computer programs are created by swapping and recombining random segments of two programs. This process will produce increasingly fitter populations of programs. This process continues until an adequate computer program solution has been found or until a fixed number of generations have been run. Autonomous robots with 5 functional behaviours with inputs from sonar sensors were tested. The initial program population comprised of 4 primitive functional functional behaviours representing STROLL, AVOID, ALIGN, CORRECT comprising some 150 program functions such as move "back a fixed distance", "turn right/left a fixed angle", "move forward a fixed distance", etc. The purpose was to evolve the subsumptrion architecture. The subsumption architecture may be represented by the IF conditional to implement a decreasing priority of behaviours:
If S_1 then CORRECT
If S_2 then ALIGN
If S_3 then AVOID
If S_4 then STROLL
Fitness was defined as the maximum coverage of wall perimeter in the shortest time. The best 10% of parents surviving into the next generation intact and the crossover was applied to the other 90% of the programs to create new programs. A computer program was succesfully evolved which exhibited the subsumption architecture via the composition of the conditional IF statement in performing wall following of an irregularly shaped wall.

De Garis (1991) used GA's to evolve neural network modules (GenNets) to construct hierarchical control systems. Each artificially evolved neural net is regarded as a functional black box which performs a specific behaviour, ie. a specific control system. Fitness is a measure of the quality of the behaviour. Each neural net module input is connected to each sensor and each output unit is connected to each motor. Synaptic weights and thresholds can be coded and evolved as genetic algorithm chromosome values. The GA has better convergence properties than gradient-based techniques such as backpropagation in the face of noise, reducing training times by two orders of magnitude. The GA searches the solution space globally while gradient techniques perform local searches in the vicinity of the current solution. It finds the best combination of connection weights rather than just each weight independently. A population of genetic algorithms has a proportion (typically 20%) which survive through cross-over into the next generation undergoing 10% random mutation. A typical fitness criterion for a wheeled rover is given by:

$F = V + (1 - \sqrt{DV}) + (1 - I)$ where V=average rotation speed of opposing wheels
DV=difference between signed speed values of opposing wheels
I=activation value of the sensor with the highest

Input

This maximises speed, movement in a straight line and avoidance of obstacles. A wall-following fitness function may be encoded as:

$$F = \frac{1}{T}\int_0^T \left(e^{-k_x C_x(t)^2} + e^{-k_y C_y(t)^2} - s(t)\right)dt$$ where $C_x(t)$, $C_y(t)$=distance from centre of arena

k_x, k_y = Gaussian function such that
= 1.0 at centre
0.1 at wall
s(t)=0 if moving
=1 otherwise

The fitness function should compute information that is available to robot through its sensors only – for planetary surface exploration, vision sensing is required so that the fitness function can incorporate maximisation of mean free path and speed with minimum energy consumption. The N neurons of the neural net are labelled 1 to N (N~10-15 being typical) and N^2 interconnections if the net is fully connected. A number of binary places P are allocated to specify the weight values and one bit to specify its sign. For N^2 connections, the binary string requires $N^2(P+1)$ bits to specify all the connection weights. It is possible therefore to specify the GenNet from its chromosome representation. GenNet modules may be constructed into hierarchical structures to exhibit arbitrarily complex behaviour. Each GenNet with its specific behaviour may be evolved separately and then organised appropriately. Control GenNets are used to direct and command functional GenNets in that the outputs of the control nets serve as inputs to the functional nets. Control GenNets are evolved once the functional GenNets have been frozen. Such hierarchical control may be multiply layered. This methodology has been applied to an artificial lizard, LIZZY which reacts to three types of creatures each of which emits a characteristic frequency: mate, predator and prey. Its behaviour varied according to the signal it received and its strength (indicating its distance) via its a suite of detector, logic and effector GenNets. GenNet weights were stored in ROM and the weights were used to connect up and control physical detectors and effectors.

Mataric & Cliff (1997) evolved GA-based neural network controllers from a simulator which can be downloaded to the real robot. If evolved in simulation, there will be a mismatch between simulated and real sensory data. Simulation does not describe the physical laws of interaction in the real world and physical sensors and actuators are subject to uncertainty. However, after initial evolution in the simulated environment, only a few additional generations are usually required to achieve successful behaviour in the real world – adaptive fine-tuning. It is required that the level of noise in the simulation matches that of the real world. Most of the evolutionary process is performed on the simulator with a further few generations of evolution on the robot itself. The use of simulation significantly speeds up the learning process. Typical tasks included obstacle avoidance and goal-seeking. Grasping behaviour also has been achieved using a 5-input/4-output neural network. The inputs were from two frontal sensors, left and right sensors, and a gripper sensor. The outputs included two wheel velocities, pick up procedure and release procedure. The fitness function included parameters concerned with robot-target distance, target position relative to the robot, presence of an object in the gripper and its release, etc. Learning gripping behaviour was more complex than most other rover-type behaviours as it involved a multitude of sensors and tasks including moving the robot close enough to the target to be grasped. The fitness function became complex and subgoals were embedded in them to produce the required behaviours. The species adaptation algorithm (SAGA) may overcome this problem by utilising variable length genomes [Husbands et al 1997]. Initially, short simple genotypes may be used to generate elementary behaviours, and the length increased until sufficiently complex behaviours are evolved. A specialised cross-over procedure is used with these variable length genomes. Further work has involved the evolution of visually guided behaviours on GA-based recurrent neural network control systems incorporating exitatory and inhibitory mapping between vision and actuators [Husbands et al 1997b]. A number of circular receptive fields of given radius and angular position rϕ are represented on the genome which provides the basis for interpreting visual inputs through the construction of vector flow fields representing robot motion. Incremental evolution whereby increasingly challenging tasks are solved sequentially rather than always starting from random populations offers better performance.

Genetic algorithms can be used to evolve neural network controllers for robots, and indeed, their morphology [Mataric & Cliff 1996, Harvey et al 1997]. This is evolutionary robotics whereby neural network architectures are encoded as genotypes. Most commonly, the number of internal hidden units, connection directionality, and number of connections are encoded. If morphology such as number, size and position of visual receptive fields are also included, they are encoded in a modular fashion into their own chromosomes. An initial population of different genotypes each encoding a robot control system are randomly created and the fittest robots are allowed to reproduce by generating copies of their genotypes through reproduction and cross-over (with cross-over probability of 0.5) with a small level of mutation [Santos et al 2001]. Over successive generations better performing controllers are evolved. The neural network is ideal for implementing the evolved control structure as it offers smooth search space and are biologically plausible. Recurrent neural networks provide temporal properties that allow the evolution of non-reactive behaviours. Dynamic recurrent neural networks are discrete with clocked time delays rather than continuous behaviour. Dynamic recurrent neural networks are equivalent to augmented finite state machines. One characteristic is that low cross-over rates should be used to minimise repeated structures. The genetic algorithm codes for the neural network properties such as number and types of neurons and their connectivity. The Elman recurrent neural network with sigmoid functions on the output units represents the phenotype whose architectural properties are encoded in genotypes, eg. a type 3 Braitenburg vehicle (embodied as a Kephera micro-robot) comprises a number of forward and rear infrared proximity sensors on the input layer fully connected to two-neuron output layer which drives the motors. Outputs are motor signals such as full ahead, half ahead, stop half reverse full reverse – skid steering provides directionality. With the number of input and output units specified, there are an arbitrary number of hidden units and connections may be excitatory or inhibitory. The Elman architecture included a bias unit to ensure output even in the absence of sensory input. An attractor fitness function may be defined as: $F = \sum_{\forall t} e^{-s/|r(t)|^2}$ where r=distance of robot from attractor and s=scale factor to penalise large r. The fitness function was defined as [Mondada & Floreano 1995]:

$F = v(1-\sqrt{\Delta v})(1-s)$ where v=average velocity of two motors
Δv=difference in two motor velocities
s=normalised activation level of proximity sensor

The first term rewards speed, second rewards straight trajectory and the third rewards obstacle avoidance. Reasonable behaviours from an initial population of 50-100 or so individuals were evolved after 50 generations and excellent behaviours were evolved within 100 generations. A Kephera with a battery life of 20s was tasked to move around in an enclosed arena while maintaining its battery charge by visiting a visually marked battery charging area when necessary for recharging. Fitness favoured maximum travelling distance. The neural network controller was a multilayer feedforward recurrent neural network with one hidden layer. The simpler fitness function was defined as:

$F = v(1-s)$ where v=average rotation speed of two wheels such that $0 \le v \le 1$

s=voltage level in battery such that $0 \leq IR \leq 1$

The energy received by the robot is defined by: $\Delta E = E_{const}(1 - E(t)^2)$. The fitness function favoured rapid movement while the environment imposed the necessity to periodically recharge. Within 240 generations, a successful individual was evolved which recharged roughly every 19s but avoided it otherwise. Genetic algorithms have been used to evolve recurrent neural network controllers for simulated insect. The neural network was evolved for locomotion. Simulated hexapods and their gaits (stance and swing phases) are encoded in terms of motor activity and sensory values. Six legs, each with a foot that may be up (swing) or down (stance), swing horizontally (forward or back). The hexapod must maintain static balance on three feet with its centre of mass within the triangle of its three feet. Each leg is controlled by a fully connected recurrent neural network that receives input from angle sensors to measure leg angles relative to the body. Each leg employs a network of 5 continuous sigmoidal nodes with full connectivity, each node receiving an input from an angle sensor (one for up/down foot, one for forward swing, one for backward swing, and the other two unconnected interneurons). Each of the 6 networks were connected only to their neighbours. This represents a direct encoding scheme. The genetic algorithm evolved the neural networks for controlling the hexapod and indeed, evolved the tripod gait. The robot successfully evolved a neural network controller which performed the required behaviour. As evolution time correlates with the complexity of the task, scalability of evolutionary neural nets is suspect. However, incremental evolution from simpler environments and fitness functions and gradually increasing the complexity of tasks and selectivity of fitness functions appears to be a reasonable solution - shaping. For instance, the complex Nomad robot used a classifier system to evolve behaviours such that the start and goal positions were held fixed while obstacles were varied to prevent learning a map. The inputs were the sensors and the outputs were speed and direction. It is essential that the simulation matches the real environment in order to evolve matching behaviours. In particular, if the noise levels in the simulation differ from those in the real robot-environment, evolved behaviour from the simulation will not be transferable to the real robot-environment. In both cases, for lower and higher noise levels in the simulation compared to the real robot, there will be mismatches that make the evolved controllers non-transferable into the real world. The noise levels must be matched to allow transfer of evolved controllers from simulation to the real world. In particular, it is advantageous to utilise real sampled data from sensors. In this case, fine-tuning the evolutionary process in the real world is necessary. It is necessary to model only those characteristics of the robot-environment interaction that are relevant for the emergence of a desired behaviour – base set features which must be accurately modelled. There are other implementational aspects which have no bearing in reality which should be randomly varied to simulate noise. The base set should also be varied periodically to allow for variation in the environment. This Jakobi methodology is constructed from the following steps:

(i) base set of robot-environment interactions must be identified and modelled
(ii) implementational aspects must be varied randomly in each trial to ensure that they are not relied on
(iii) base set must be randomly varied in each trial to reflect environmental variations

Vision sensing is characteristically more complex than simple sensors in robotics but ecological approaches offer rapid computational capabilities by closing motor feedback loops. Furthermore, vision is the dominant sensory modality in the animal kingdom for gathering distal data in the environment. The simplest vision sensor is two photoreceptors either side of the longitudinal midline but insects have more complex eyes. Each photoreceptor is characterised by its rϕ space where r=distance of eye from target, and ϕ=angle between radial line from target to eye and optical axis of photoreceptor [Cliff et al 1993]. The CCD image grabbed and filtered may be connected directly into the input units of a neural network [Cliff et al 1993]. A vision simulator based on ray-tracing simulates the photoreceptor array fields of view typical of insects with only a few rays per photoreceptor. The visual input can be reduced by sampling only a small part of the image according to genetically specified instructions. Each individual in the population is characterised by two chromosomes: one of fixed length specifies visual morphology, the other the neural architecture. The visual chromosome encodes the size (discretised acceptance or field of view) and positions (discretised eccentricity) of three receptive fields, each receptive field being a circular image patch with a diameter and centre position. For each receptive field, 25 pixels uniformly scattered over its area are selected and their values averaged to generate a 4-bit single value. The three values – diameter, centre position and average pixel – are input to the neural network. A fitness function to avoid one type of object and move towards another type of object was given by (differentiable visually):

$F = \sum_{i=1}^{n}(\alpha d_{1i} - \sigma d_{2i})$ where d_{1i}=distance from attractive target

d_{2i}=distance from obstacle

The fitness function should describe only the final task that the agent must perform rather than a detailed prescription of how to achieve it. Grasping with simple manipulators is a useful function. Rather than specifying trajectories, object recognition, etc, the fitness function F=n where n=number of objects gripped within a test period [Mondada & Floreano 1995]. The evolving neural network had three outputs (two positioning motors and one grip action). There are a number of ways in which performance can be increased [Nolfi & Floreano 2002]:

(i) increase the frequency of sensory states
(ii) select non-overlapping sensory states to enhance discrimination

Type 2 problems are those which are hard as mapping input patterns to output patterns is complex as regularities that allow such mapping are hidden. This is to be differentiated from type 1 problems which are easy and rely on detecting regularity and differentiating features with sensory data. Type 2 problems can be reduced to type 1 problems by appropriate recoding [Clark & Thornton 1997]. One way to do this is to break the problem down into simpler sub-problems and train on those tasks first before training for the complex task. The first learning phase effectively recodes the sensory patterns to extract their regularities. This shaping the fitness function may be one approach to accelerating evolution in more complex robot-environment situations. It may also be possible to re-adapt evolved neural net controllers on simple robots onto new morphologies such as more complex, larger robots, eg. from Khepera to Kaola. The evolution of a garbage collection neural controller with a gripper required recognition of targets and more complex behaviours based on an emergent modular architecture. These modules do not correspond to different distal behaviours independently rather different modules contribute to the implementation of different behaviours. They tend to act to produce different motor responses for similar sensory states, ie. enhance the ability to discriminate between sensory patterns. Predator-prey type competing co-evolutionary systems with coupled fitness to generate an evolutionary arms race are an approach which may be scalable (red queen effect). The two populations compete and co-evolve against each other – one population is selected for pursuit while the other is selected for evasion. For instance, the evolution of egg mimicry and egg discrimination in birds are subject to co-evolution with the incidence of brood-parasiticism (eg. cuckoos). The life/dinner principle suggests that selection pressure on prey is stronger than on predators. Furthermore, each member of the population is spatially distributed so that only adjacent neighbours can breed with each other. Predator prey dynamics are described by the Lotka-Voltera equations which lead to oscillatory populations. Such techniques have not yet been used for co-evolving robot controllers except for social interaction behaviours [Bullock 1995]. Latent energy environments might have particular applicability here: energy is acquired through catalytic reactions between two atoms: $(A_i A_j) \rightarrow E_{ij}$ while running out of energy causes death [Menczer 1994]. A limited form of co-evolution can occur between subpopulations of genomes such as encoding for control systems and visual morphologies, eg. evolution of higher density of receptors in the front of the agent than in the rear [Nolfi & Floreani 2002]. Additional parameters that may be encoded and subject to evolutionary selection include body size, baseline, wheel size, etc. Further developments provide for the evolution of material structure of thermoplastic through 3D printing.

The phenotypic parameters for the controller must be encoded within the genetic algorithm. The simplest encoding scheme is a one-to-one mapping between genotype and phenotype such that each gene codes for a single character. The encoding scheme must be robust with respect to the genetic operators such that mutation and cross-over should yield similarly fit offspring to the parents. The chief problem with encoding neural networks is that their dimensionality often needs to be pre-specified. However, the network morphology may also be subject to evolution. The genotype may specify a grammar (such as L-systems) similar the development process which maps genetic code to the phenotype. The Sims approach represented morphology as a directed graph and form a variety of structures including fractal ones. The genome comprised of Lisp logical units defining equations (arithmetic commands of add, subtract, multiply, sine, cosine) rather than digits. Using these primitive mathematical operations, it is possible to build all possible equations. As any shape can be defined mathematically, any picture can be constructed. Connections between nodes encoded properties such as position, orientation, scale, etc which may be mutated. Nodes contain information about dimensions of components and connectivity to other nodes. These graphs encode properties of the controller and the robot's morphology. Initial genotypes are generated randomly and subjected to co-evolution. Morphological components are replicated and mutated. There were three mating operators: 40% asexual, 30% cross-over and 30% grafting. The use of L systems for encoding requires more complex genetic operators. The species adaptation genetic algorithm (SAGA) allows for variable length genetic algorithms whereby the genome length correlates with the complexity of the phenotype. The variation in length is determined randomly but if longer genotypes offer increased fitness then they are retained. Similarly, vice versa for shorter genomes. Short genomes suitable for simple behaviours can increase in length to accommodate more complex behaviours, ie. a species evolution. Rank or tournament based selection is used to ensure optimal mutation/selection rates such that the expected number of offspring of a member of the population is dependent on its current ranking and mutation rates are set at around 1 mutatin per genotype. Encoding schemes should also accommodate repeated structures and modular encodings provide this similar to automatically defined functions used in genetic programs. Such encodings should be complete, compact, closed, modular, scalable and expressive. They emulate growth during embryonic development. In Gruau encoding, the genotype specifies a sequence of graph-rewrite operations applied to an initial graph of a single neuron. The rewrite operations generate more neurons forming a binary tree structure through cell division. Gene-splicing divides the genome into a number of separate trees in a hierarchy with terminals defining subroutine calls to lower nodes. Thus the tree hierarchy provides for modularity. Edelman's Neural Darwinism models ontogenetic processes (learning) through selectionist principles. Neural growth is the basis for feature detection development stabilised by developmental selection followed by phenotypic selection to generate categories. Re-entrant maps and degeneracy allow categorical perceptions of different objects to be compared and assigned to classes. The repertoire of features and classes is based on statistical correlation and similarity matching. Coupled maps – generalised cellular automata with continuous rather than discrete values - are suited to expressing recurrent patterns between source and target variables [Steels 1997].

There are a number of techniques which involve the use of evolutionary techniques for the development of neural controllers for mobile robots [Mataric & Cliff 1996]. Although neural controllers have smooth fitness landscapes, genetic programs and classifier systems offer coarser landscapes which favours the use of reproduction operators rather than mutation. Classifier systems have been used for evolving controllers whereby incremental learning was implemented through shaping. In simulation, the technique was first applied to learning basic behaviours and then learning to coordinate them for behaviour selection. The simple robot AutonoMouse used a hierarchical organisation of classifiers to evolve simple behaviours to follow a light first by orienting to a static light then moving it. Such shaping accelerates learning. Genetic programs utilise high level programs such as Lisp S-expressions for the evolution of navigation behaviours and have demonstrated the evolution of subsumption-based controllers based on a fitness function which counted the number of near wall squares visited. To control complexity, the depth of initial random S-expressions was limited to 4 and that of crossed-over expressions to 15. Genetic programming has successfully been applied to box-pushing robots.

Handley (1993) introduced Genetic Planner which used GA-based artificial selection to breed computer programs that generate plans to purposively control a mobile robot. The genetic planner used crossover recombination and artificial selection through a fitness measure to breed computer programs. A world model comprised a set of procedural operators which operated on the set of predicates that defined the world model. The world model predicates were of the form: at(object,x,y), with-respect-to(object1,object2). The procedural operators included: “turn left/right 90”, “move forward a fixed distance”, etc. The fitness function was defined as a distance between objects measure. The agent used the procedural operators to generate robot action plans utilising a goal-oriented fitness measure and a world simulation. The genetic planner used the operators to execute candidate computer program plans and the fitness function evaluated the state of the world after each simulation. As the genetic planner did not reason about the world, it randomly generated plans and ran them until it came up with effective plans. This type of capability has use in trajectory planning.

Learning supplements evolution by allowing organisms to adapt to their environment within their lifetimes. Genetic evolution is based only on a single criterion – reproductive success while learning can be tuned to a wide variety of specific tasks. Through the Baldwin effect, learning can guide evolution – evolution tends to select individuals who have genetic features that would otherwise be learned through the indirect genetic assimilation of learned traits. Learning however is costly in that it takes time and may be inappropriate under certain conditions. Learning makes the fitness landscape smoother enabling easier progression to otherwise inaccessible peaks.

A biologically-inspired computational connectionist model of the cerebral cortex with perceptive, motor and associative functions has been presented [Frezza-Buet & Alexandre 2002].

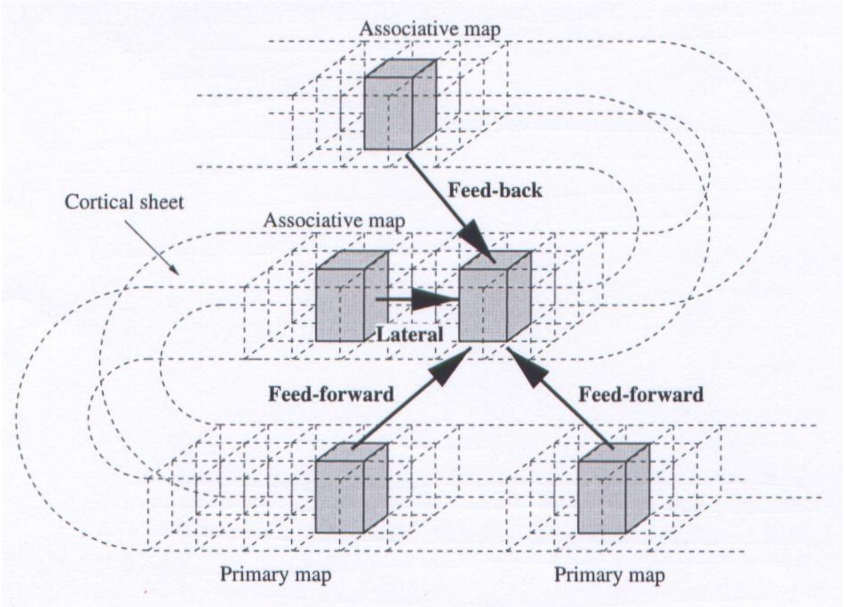


Fig 7-9 Kinds of information flow within a maxicolumn [from Frezza-Buet & Alexandre 2002]

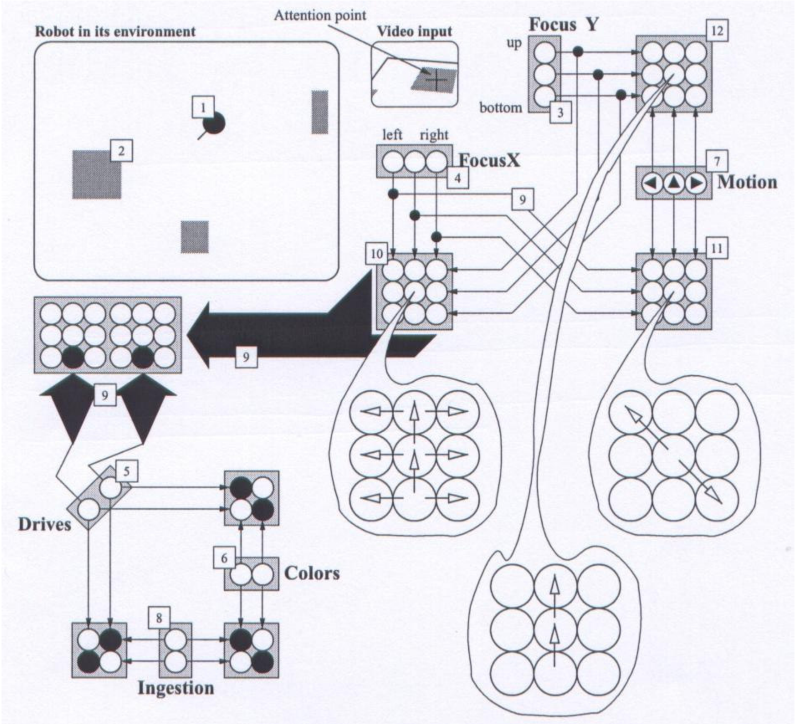


Fig 7-10 Association cortex of an animat: (i) animat; (iii-v) sensory areas; (vi-viii) motor maps; (ix) feedforward; (x) associative visual map; (xi-xii) associative motion maps [from Frezza-Buet & Alexandre 2002]

It models the cortex as a series of overlapping functional maps – unimodal sensory and motor maps and multi-modal association maps. It implements three type of information flow –

feedforward signals from the input into association regions, feedback signals in the reverse direction, and lateral flow which implement inhibition and sequencing. The human cortex is modular in organisation based on the cortical column of ~100 neurons which can learn to act as specialised filters, eg. visual cortical columns respond to specific orientations of visual stimulus. The model implements maxicolumns as sets of columns which are tuned to perform different operations on the same input through self-organising maps which extract prototypes, eg. different orientation selectivity in a visual system. Association maxicolumn performs logical AND between its inputs and so detect co-occurrences of different perceptual events. The maxicolumn represents a specific event to which it is tuned through the sensory map through lateral inhibition and the activity spreads through feedforward and feedback to other association and motor maxicolumns to generate actions that achieve a desired goal – in this way, weighted causality chains are built backwards through Rescorla-Wagner rules such that unconditioned stimulus is associated to a conditional stimulus that predicts the unconditioned stimulus. The model provides a robust mechanism for action selection for a simulated animat and includes drives (internal state of the animat) for online learning implementing procedural memory (modelling the primary association areas of the posterior cortex), episodic memory (modelling the hippocampal system), and planning memory (modelling the function of the prefrontal cortex).

7.6. HYBRID APPROACHES TO CONTROL

An autonomous system requires both goal-oriented planning and robust reaction. In short, the need is to hybridise or integrate the "sybaritic" approach which emphasises embodiment in the real-world environment through sensors and actuators and GOFAI (good old fashioned AI) which emphasises symbol manipulation as the basis of problem-solving. There remains the possibility of adopting hybrid soft computing and symbolic methods to overcome the problem of validation. Structured (knowledge-based) connectionist architectures as an approach to AI combines the paradigm of symbolism and connectionism into a hybrid system. Neural networks are particularly appropriate for pattern recignition tasks when taining examples are available for learning. Scaling up to realistic biological neural structures imposes considerable complexity. Connectionism is appropriate to sensor interfaces, while symbolic methods are most appropriate for implementing empirical rules of behaviour, and evolutionary techniques are appropriate for neural learning and rule learning. Kim (1989) proposed that an intelligent system may be implemented through a domain independent inference engine based on first order predicate calculus which incorporates procedural knowledge heuristics. This inference engine acts upon a number of large structured, domain-dependent knowledge bases of declarative knowledge. (representing long term memory). Mode & Saridis (1990) suggests that the Boltzmann architecture of the neural network may be suitable for cognitive modelling – input nodes represent goals, output nodes represent primitive behaviours while the hidden nodes represent their interaction, one combination of which represent the optimal plan. Minimisation of the energy of the Boltzmann machine configuration corresponds to the minimisation of entropy representing the optimal plan. Such miminisationmay be performed using genetic algorithm searches. However, these hybrid approaches are not proposed as models of human reasoning but they can perform both pattern recognition and logical inferencing by implementing approximate reasoning. Indeed, skills learning may be characterised as a transformation process from serial inferencing to parallel pattern recognition.

Structured connectionism uses a local representation structure of coarse-coded knowledge-based expert system on the basis that distributed representations of concepts suffer from cross-talk, limited information capacity, and inter-communication problems [Feldman et al 1988]. Furthermore, brain structure indicates a degree of localisation and specialisation. On the other hand, a distributed representation of high robustness to error. Nodes representing complex logical rules are expanded into subnetworks of atomic variables. The use of a hidden layer between input and output layers allows the implementation of any boolean logic function AND, OR, NOT, IF…THEN. The rule "if…then" defines the weighted connection between two nodes. Simplification of network nodes into atomic primitives offer greater resolution of connections for learning. A multilevel hierarchy may be constructed as a kind of linked list structure. Fully connected structures offer maximum flexibility. The separate layers act as a global clock and activation of the network follows an event-driven dataflow model. It is then possible to construct ANNs for any production rule to form synthetic expert networks where ANN functionality is defined in terms of inference rules. The knowledge based expert system offers logical inferencing, transparent behaviour and expressiveness, modular structure of separate knowledge base of production rules, inference engine and working memory. The structured connectionist approach has each concept/proposition (production rule) represented as a neuronal unit with connections to other neuronal units with linking consistent with domain knowledge – this represents a kind of associative memory or inference net. Each condition/antecedent is assigned an input node and each conclusion/consequent is assigned to an output node both of which are linked either directly or through a hidden node. Hidden units are added by default to allow complex modelling capacity. Rule strength corresponds to connection weight. The hidden unit may act to represent conjunction and/or disjunction of input conditions. Conjunction is represented by the minimum operator and disjunction is represented by the maximum operator in the neural activation functions. Conjunction nodes allow further specialisation while the disjunction layer provides the potential for generalisation. Hence, there are three layers of condition-conjunction/disjunction-conclusion rules [Fu 1993]. Conversion between boolean neural network structures and Horn clause format is straightforward. The cells form a dependency network of input, intermediate and output concepts. Control is distributed amongst the neuronal units and the activation state of the network describes the internal states of the network. The links are weighted to reflect the semantics of the knowledge base. Learning is enabled through weight changes by initially assigning known values to input nodes while others are assigned unknown values. New values of each node can be determined according to the learning rule. This highlights the difference between the ANN and the semantic network. Semantic networks are suited to hierarchical world models. Semantic links indicate logical relations between concepts while ANN links are weighted paths resembling value-processing pointers. The relative strengths of conflicting conceptual/propositional units may be combined using a probability-based Bayesian maximum likelihood function of evidential reasoning may be adopted representing probabilistic confidence/certainty factors and partial rule matching. The weights give an indication of the certainty factors for correct inferencing to accommodate uncertainty and plausibility. Typically, w_i=0.1 for weak rules and w_i=0.5 for strong rules. In fact, the connectionist network is a form of Bayesian belief network. Only weights are modified through learning rather than rules themselves. The deletion of a connection from conjunctive to conjunctive units causes rule deletion, and the addition of a connection from conjunctive to disjunctive units creates rules. The deletion of a connection from disjunction or addition of a connection to conjunction causes generalisation of a rule. Addition of a connection from disjunction or addition of conjunction specialises a rule. The automated acquisition of new rules may be accomplished through genetic algorithms. Any inference engine can use a weight matrix to represent the connectionist expert system [Gallant 1988]. It can perform both forward and backward chaining propagation through the network. If…then production rules are not represented explicitly but are generated in an inference network topology by the inference engine operating on the knowledge base as required from the weights. If all possible topologies were elucidated this would comprise a traditional knowledge base. One example of the connectionist expert system is Low et al's (1991) adaptive connectionist expert system trouble shooter for inertial navigation of aircraft.

Verschure & Althaus (2003) suggest that symbolic knowledge-based systems may be unified with behaviour-based methods by adopting Bayesian decision-making for knowledge-based systems and distributed adaptive learning and control for behaviour-based systems. Bayes theorem computes the probability that a hypothesis h is true given observation o and prior hypotheses H:

$p(h\,|\,o)=\frac{p(o|h)\,p(h)}{p(o)}$ where p(o)=probability of observation o

p(o|h)=prior probability that observation o occurs if h is true

Optimal action a may be computed using a score function G(h, a) which defines expected gain <g> of performing action a given hypothesis h and Bayes thereom selects action a* which yields maximum expectancy <g>:

$$<\!g\!>\,=\max_{a\in A}\left(\sum_{h\in H} p(h\,|\,o)G(h,a)\right)$$

It is reckoned that Bayesian computations are performed within the parietal cortex, visual cortex and multi-sensor within the superior colliculus. The prior hypotheses are supplied by the distributed adaptive control (DAC) learning system. DAC was a neural model of classical and operant conditioning. In classical conditioning, after several simultaneous presentations of US and CS, the presentation of CS alone will trigger the CR similar to UR. In operant conditioning, the agent learns to associate its actions with particular environmental states – the US that results from an action provides a reinforcement signal. The well-known rat in a skinner box learns to press a lever (CR) to receive food (US). DAC implements three control layers – reactive with prewired reflexive sensory (US)-motor (UR) rules; adaptive control layer that allows learning of complex conditional events (CS) on US events; contextual layer which develops more complex representations of CS and CR events temporally. DAC in fact uses its contextual control structure in a Bayesian fashion to achieve its goals and its symbols are emergent from the decision making based on local rules.

Maes (1990) suggested that explicit goal handling with reactive capabilities eliminate the need for re-planning or re-programming with altered goals. Goals effectively bias choices of action (action selection). One approach to such action selection is through emergence via the local interactions between action-oriented modules. Each module represents an operator of the classical planner and may be described by the triple $(c_i, a_i, d_i, \alpha_i)$ where c_i=pre-condition list, a_i=action effect list, d_i=action effect delete list, α_i=activation level. The module is executed when all the pre-conditions are true and the activation level exceeds the threshold. Modules are linked into a network with three types of link between modules: successor links, predecessor links and conflictor links. Successor links exist when every proposition p that is a member of x's add list is also a member of the pre-condition list of y. Predecessor links exist for the inverse relation. Conflictor links exist when every proposition p that a member of the delete list of y is also a member of the pre-condition list of x. Modules use these links to activate and inhibit each other with inhibition providing the means to deal with interacting sub-goals. Activation energy is determined by the input from the current situation according to its match to modules and by goals which determine the activation threshold of goals. Protected goals remove activation from modules that would undo them. Spreading activation across the network of modules equilibriates to the best actions determined by the current situation and the current goals of the agent. Successor links propagate action forward to successor modules and predecessor links propagate activation backwards to predecessor modules by a fraction of their respective originator module activation energies. Conflictor links decrease the activation level by a fraction of the originator module's activation energy when a module undoes a true pre-condition of another module. All inputs of activation from a module is weighted by 1/n where n=number of propositions in the pre-condition/add/delete list as appropriate. As the state of the environment changes, so too do all the activation patterns. Global parameters may be used to alter the activation dynamics through threshold adjustment, input activation adjustment, goal activation adjustment, and conflict activation adjustment. The pre-conditions act as subgoals. A sequence of modules are highly activated which transform the current situation into the goal situation through forward spreading from the current state and backward spreading from the goal state. As the links are only local among modules, different paths may be evaluated in parallel. The system is a marker-passing system without variable use in that objects in the environment are represented by only those features relevant to the agent. Hence, new operator modules are not required when encountering new objects. Goals are specified in terms of functional constraints on the objects in the environment. The control structure is emergent when particular actions are activated. The interaction dynamics between action-oriented modules establish the sequence of actions in a distributed manner in response to environmental conditions and global goals. The local interactions between components forms an emergent global structure.

Mataric (1992) suggested that rather than utilising hybrid approaches with separate reactive and planning modules, it is possible to maintain a map representation based on discovered landmarks distributed over the subsumption architecture of behaviours. This represents a fully integrated approach. The robot's control system comprised of behaviours specific to basic navigation, landmark detection and map computation. Basic navigation and obstacle avoidance involved strolling forward unless an object was in front of the robot, turning away from objects, and aligning with boundaries to follow them. Landmark detection involved matching sensory data to stored landmark signatures. The mapping algorithm mapped the structure of the environment based on the spatial relationships of the landmarks. The map was coarse and encoded as a topological graph with each node representing a landmark and the links representing adjacency. Each landmark was a behavioural set of rules and the links operated as message-passing connections. Each landmark behaviour received inputs from the landmatk detector, while sending outputs to other landmark behaviours. Loccalisation involved comparing stored landmark signatures with the current sensory data. Expectation was generated by spreading activation through the graph, so adjacent landmarks were primed forming a path to the goal landmark, ie. path planning.

Handelman et al (1990) introduced a robot control methodology modelled on human motor skills learning. There are three phases of skills learning of sensorimotor reflexes:
(i) The early cognitive phase where the task is approached consciously through inferencing by the beginner;
(ii) The intermediate associative phase where response patterns begin to emerge;
(iii) The final autonomous phase when the execution becomes automatic and reflexive for the expert.

The skills learning process includes a shift from conscious declarative processing to automated procedural processing, ie. the declarative representation becomes "chunked" into a more condensed procedural representation through a compilation mechanism. An alternative representation of motor skills acquisition is through the repeated associative learning of input/output pairs which gradually determines the connection weights of an artificial neural network which becomes fixed on completion of the learning process. Such a method of implementing motor skills learning to robots should offer high levels of dexterity and adaptability. A three-level hierarchy was defined for fproviding reflexive behaviour. A rule-based execution monitor teaches a CMAC (cerebellar model architecure controller) network how to accomplish a task by observing the rule-based task execution. The knowledge-base represents declarative knowledge with inferencing abilities while the neural network represents associative procedural knowledge with pattern matching abilities. The neural network effectively captures the causal relationships between the robot and the environment. The knowledge base determines how to accomplish the control objectives using the rules. These rules include the learning strategies, task execution processes, network training data and performance monitoring. It teaches the neural network to accomplish the same tasks by allowing them to observe the task execution. They learn through generalisation at which point they assume control responsibility. The nural net then fine-tunes its performance during task execution through reinforcement learning. The knowledge base continuously evaluates the networks performance. If errors occur due to the changing dynamic environment, the knowledge-base is re-engaged and the network re-trained. The basic control system implements low level servo-reflex on the innermost loop, reflex modulators in the middle loop to provide gain adjustment, and execution monitoring to supervise reflex modulator learning.

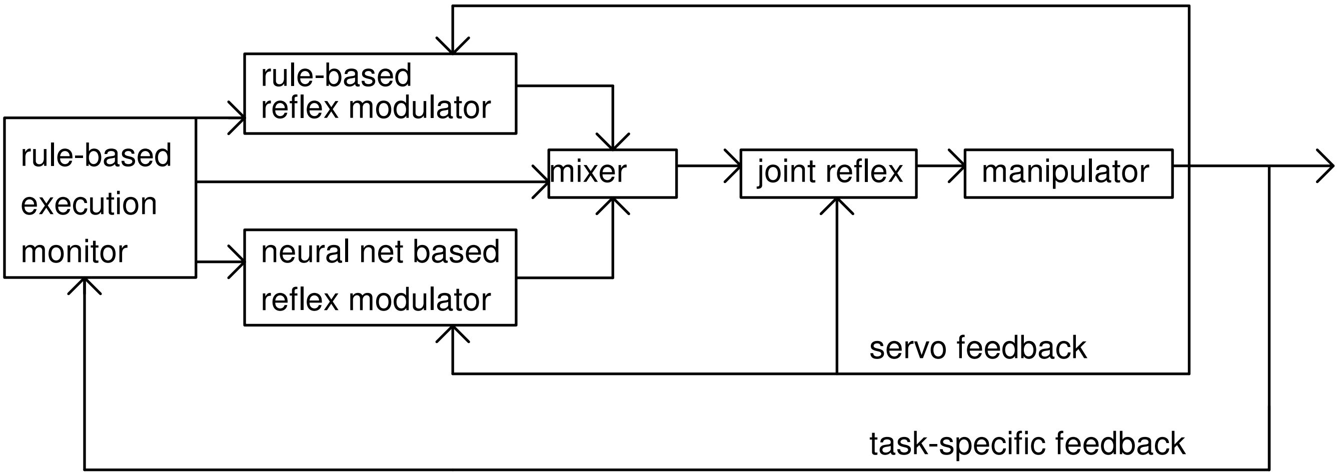


Fig 7-11 Motor skills learning architecture (from Handelman et al 1990)

The servo-level implements a standard computed torque control law. The rules in the knowledge-base are independent of the dynamic model of the manipulator. A goal-directed backward search is implemented by an inference engine through the knowledge-base of parameters, production rules and procedures. Parameters are values relevant to the control objective while the rules express relationships and dependencies between parameters. Within the conditions and actions are procedures that invoke time-critical control tasks such as low level joint reflexes and control laws. The rules provide the means to build higher level control actions out of the procedure building blocks to generate coordinated motion. All maneouvres are implemented as a series of steps. The neural network implementation is a CMAC which performs a perceptron-like table lookup for generating nonlinear mapping functions between multiple input-output variables. The knowledge-base control executor provides the means for it to learn by example. The necessary generalisations of sensorimotor behaviour are accomplished through connection weight adjustments via a steepest descent updating algorithm. The CMAC learns to duplicate the rule-based reflex commands. When the CMAC's outputs match those of the rule-based outputs, learning ceases and the CMAC outputs directly to the joint reflexes during manipulation. Once trained, the input values cause the CMAC to output control gains and commands to the servocontrol system of the manipulator. Thus the CMAC reflexively executes the required muovements. If the CMAC output deteriorates subsequently, control switches back to the knowledge-base while CMAC undergoes further learning. Hence, knowledge-bases can be used to supervise and train artificial neural networks and indeed, the neural network offers a more robust performance by fine-tuning its performance through reinforcement learning. It is a highly promising technique for use in space-based systems as it offers an integrated approach utilising the neural net for its robustness and the knowledge-base as a reliable backup.

Fuzzy sets provide the basis for dealing with uncertainty, relativity and vagueness in human linguistics. The meaning of a concept is determined by its fuzziness. The fuzziness of a concept is the degree to which the concept equals its own opposite, ie. A = ~A such that the concept A smoothly transitions to its opposite ~A. A fuzzy system comprises a large collection of fuzzy rules: fuzzy rules are the form “if…then…”. These fuzzy rules may be manipulated by rules of logical inference. The simplest rule of logical inference is the modus ponens rule: if P then Q; P is true then Q is true. The modus tollens rule of inference is similar: if P then Q; Q is not true, then P is not true. These rules are modified by fuzzy logic as it is no longer the case that A≠~A. They may be incorporated into neural network architectures in a hybrid technique. The neural network learns from experience and stores the fuzzy sets of a concept – they act as association memories in which information is distributed through the network. This is similar in spirit to Bayesian networks which adopt probability weights in the connection links to model cause-and-effect concepts. Least mean squared search is a gradient-descent algorithm for reaching equilibrium in the neural network. The chief problems with neural networks are scalability, re-learning from scratch, pruning to remove low performing synapses. Simulated annealing is one means through which to avoid local minima. It alters the search pattern from pure random search to pure greedy search by lowering the “temperature” of the search. However, simulated annealing is slow with a time temperature schedule of $T(t) = \frac{c}{\ln(2+t)}$ for large c. Genetic algorithms essentially applies simulated annealing to populations of genes in parallel across the search space. A neuro-fuzzy system tunes the fuzzy rules while a geno-fuzzy system tunes the fuzzy rules. Both supervised and unsupervised neural learning are applicable to neuro-fuzzy systems.

8. Spacecraft Communications & Electronic Systems

8.1. INTRODUCTION

Telecommunication components for a particular spacecraft are chosen in response to the requirements of the mission it will perform. The communication system of a satellite consists of a variety of components each one suitable for a particular task. The main interface for sending and receiving data on a satellite are the antennas. The antenna can either be of a high-gain, which is a dish-shaped spacecraft antenna principally used for high rate communication with Earth. That type of antenna is highly directionally with an accuracy of only a fraction of a degree of Earth. These types of antennas are the biggest ones in size on board the spacecraft and are either steer able or fixed to the spacecraft bus. Alternatively low-gain omni directional antennas can be used to provide low data rate at close range. It is very common in modern spacecrafts to have both types of antennas on board.

The transmitter which is on-board the satellite, is an electronic device that generates and amplifies the signal at a single designated radio frequency which is the carrier wave. The carrier wave can be sent from the spacecraft to Earth as it is, or it can be modulated with a data-carrying sub carrier. The transmitter radiates the resulting signal, which is called downlink, from an antenna. The receiver on the other end of the connection receives the incoming radio signals, demodulates them if modulated, filters out the noise and strips out the signal of its command-data-carrying sub carrier which is converted into binary code. Similarly the receivers on board the satellite function in the same way. The data is received from the ground station, striped converted into binary and passed to the spacecraft's command and data subsystem. Then the on-board systems execute the commands. Frequently, transmitters and receivers are combined into one electronic device which is called a transponder.

More detailed the basic transponder elements according to signal flow from the receiver to the transmitter are:

- Receive filter
- Low noise amplifier (LNA)
- Mixer
- Input Multiplexer
- Channel Amplifier
- High power amplifier (HPA)
- Output Multiplexer
- Output filter
- Antenna Feed for transmission

A very important characteristic of the communication system are the various amplifiers used. Based on the linearity of their operation and the noise levels the quality and reliability of the connection is determined. Special designs are made in order to accommodate a series of amplifiers in a row to achieve the lowest noise and highest gain possible.

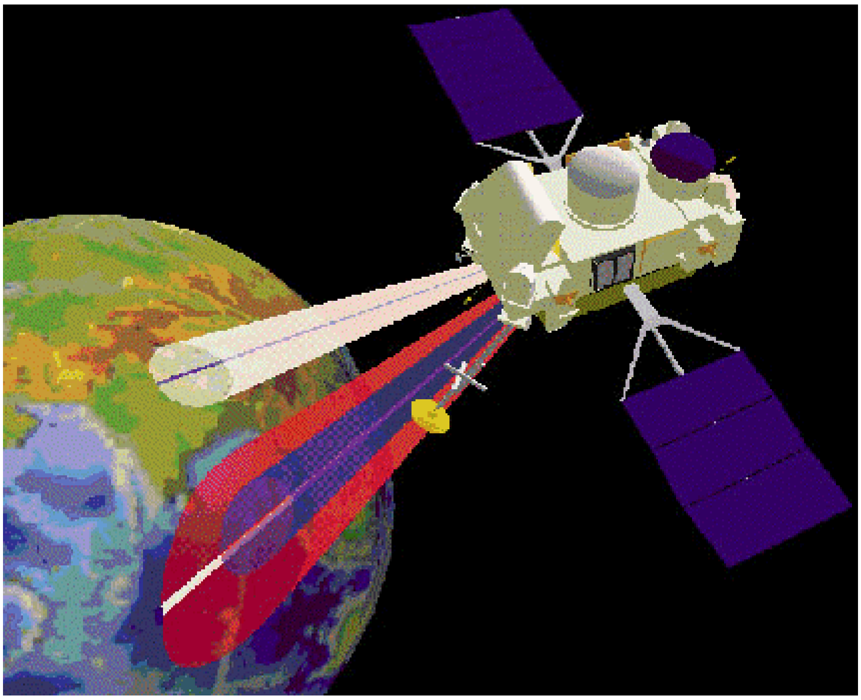


Fig 8-1 Satellite communication signal path (source NASA)

The satellite communicates with the bases station in the Ku-band or in the K-band dependant of the transponder and the application. As the satellite systems have a common degradation in their systems quality, special measures have to be taken in order to avoid their frequencies interference to similar frequency bands of other users. For that reason special international agreements are made as to which frequency ranges a satellite can transmit and receive.

A satellite system will have a number of users operating via a common satellite transponder which is called sharing of resources. Special techniques are implemented to allow sharing and management of a number of different channels in multiple accesses. Each transponder though has limited resources. Four techniques are used for multiple access each one with different applications and advantages. Namely they are Frequency-Division multiple access (FDMA), time-division multiple access (TDMA), code-division multiple access (CDMA) and packer or random access. For each technique there are additional variations which apply to specific applications. Having the ability to distribute the signal from one source to many recipients (broadcasting), the applications of satellite communication systems have expanded to a very large scale. This increase of demand in satellite services draws the request for even more efficient and powerful satellite platforms.

Frequency hopping involves the carrier frequency of the transmitter hopping abruptly to different frequencies within the spreading bandwidth at certain intervals according to the pseudorandom code sequence (this requires noncoherent demodulation). Such frequency hopping is used extensively in biological communications to minimise the information transfer to predators [Richards 1985]. Modern secure communications has exploited similar spread spectrum techniques. Cognitive radio is a form of software defined radio for maximising efficiency of communication channels by detecting whether or not a rf particular band is being used and restricting transmissions through unused bands [Walko 2005]. It can also alter its communication and modulation protocols to eliminate interference with other traffic. Cognitive radio however goes beyond this and can learn from experience recognising deadzones, interference and usage patterns.

Neural networks are highly suited to solving complex problems in digital communications including channel identification and equalisation, coding and decoding, vector quantisation, image processing, nonlinear filtering, spread spectrum applications, etc [Ibnkahla 2000]. The three commonest neural architectures used are multilayer perceptrons, radial basis function networks, and self-organising maps but there exist options for combining these with genetic algorithms, fuzzy logic, etc. Their power lies in their learning and generalisation capabilities. Neural networks provide an alterbative to identification methods such as Volterra series and auto-regressive moving average models. Multilayer perceptrons have been used to model nonlinear memoryless channels such as travelling wave tube amplifiers. They have also been applied to model nonlinear memory channels such as solid state power amplifiers. Neural networks also overcome intersymbol interference, noise and distortions in channel equalisation, particularly offering complex equalisation capabilities. Error correcting codes are uniquely suited to the neural network approach as maximum likelihood decoding is equivalent to finding the global energy maximum in neural networks. This is particularly significant given the computational cost of Viterbi decoding. Vector quantisation is an efficient compression method for image coding. Kohonen’s self-organising map and backpropagation networks have in particular been applied to vector quantisation which automatically correct for distortion, including effectively implementing Karhunen-Loeve transforms [Jiang 1999].

FPGAs may be used as the medium for evolving semiconductor circuits of logic gates (evolutionary hardware). The evolutionary process exploits the physical dynamics of the circuits without the use of clocks. The genotype specifies the Boolean function performed at each logic node and the connection between nodes. This process may be used for direct evolution of a control circuit on a simple robot which generates wall-avoidance by commanding its two wheel motors depending on the signal from two opposing sonars. The controller was based on a dynamic state machine network. The dynamic state machine is similar to a finite state machine implemented on a RAM to allow transitions to be reconfigured. The temporal dynamics depends on the physical nature of the hardware. The robot controller generated wall avoiding behaviour using only 32 bits of RAM and three flipflops. The run-time reconfiguration artificial neural network (RRANN) uses run-time configuration to increase the hardware density of FPGAs by dividing the backpropagation algorithm into three sequential stages – feedforward, backpropagation and update [Eldredge & Hutchings 1994]. The feedforward stage propagates the input through the network generating an output at evey neuron. The backpropagation stage determines the output errors and propagates them backwards through the network to find the hidden layer errors. The update stage uses the rror values to compute the required weight changes. A global controller occupies one FPGA for sequencing while each neural processor of six neurons with local RAM to store the weights occupies a local FPGA.

8.2. APPLICATION SPECIFIC CIRCUITS & FIELD PROGRAMMABLE GATE ARRAYS

ASIC’s (application specific integrated circuits) are based on gate arrays providing systems-on-a-chip technology. ASICs are ideally suited to reconfigurable smart sensors to perform offset, gain, linearity and temperature checks and self-calibration routines [Taner & Brignell 1995]. Multiple functions can be integrated into a single ASIC. They are custom-built for specific tasks. They are smaller, cheaper, faster and use less power than programmable general purpose microprocessors offering some 10 times increased performance over high end workstations. They can be used to implement forward error-correction such as Reed-Solomon coding, FIR filtering, phase shift key modulation, and image processing functions like Sobel edge detection, FFT, Hough transforms. A core operation in DSP is multiplication through array processing [Petersen & Hutchings 1995]. Typically, the main CMOS processor is based on 10^6 gate integration per chip with on-chip DRAM/SRAM operating at 80 MHz clock rates. They are however, inflexible. Structured, custom gate arrays are based on a fixed library of standard elements within a grid structure. Routing is provided through adjustable channels between the fixed cells. Field Gate Programmable Arrays (FGPA) can overcome some of these limitations by virtue of their reconfigurability [Hutchings & Wirthlin 1996, Villasenov & Mangione-Smith 1997]. The use of ASICs (application-specific integrated circuits) for dedicated functions – DSP, Reed-Solomon coding, FIR filtering, PSK modulation, FFT, Hough transforms – provides maximum computational efficiency. Real-time stereoscopic vision processing requires high processing powers which can be supplied only by multi-processing architectures [Parks 1993]. Much of the processing is concerned with repetitive low-level algorithms – matrix computations, convolutions and FIR filtering – to which dedicated DSP (digital signal processors) can be applied. Stereovision is central to the construction of a DEM (digital elevation model). General purpose processors include the SPARC processor and the T800 transputer. The INMOS transputer architecture offers up to 20 Mbps serial communications capability to support multi-processing architectures such as pipelined processing which is particularly suited to image processing. DSP processors such as the 32-bit Motorola DSP96002 includes on-chip single cycle multiplier/accumulator, integer ALU and data address generator for computation and multiple memories and data/address buses for support functions for 100 MFLOPS performance. DSPs are essentially ASICs, eg. GPS PDS16488 2-D convolver and INMOS A100 FIR filter. ESA has adopted radiation-hardened ASICs for a number of TT&C and OBDH functions in an ultralightweight package of only 15g.

Alternatively, FPGAs may provide greater flexibility. Programmable logic devices comprise an array of AND gates which generate product terms from the inouys and use an array of OR gates to generate the outputs. They can be PROM, PAL (programmable array logic), or PLA (programmable logic arrays). CPLD (complex PLD) comprises programmable multiplexer or memory cells and an interconnection network. FPGAs comprise an array of logic cells and input-output cells with each logic cell consisting of a universal function (multiplexer, demultiplexer and memory). FPGA's are SRAM-based devices which allow reconfiguration of hardware dynamically on the fly. The FPGA comprises a set of logic circuits like any other microprocessor chip but the logic circuits are not hardwired as they are connected to an array of switches (similar to a crossbar bus of bidirectional switches) that can be controlled by a compiler program. They are characterised by the regular structure of the gate array of 2D digital hardware cells. The FPGA comprises of a number of interconnected processing elements with 100,000 gate/chip level of integration forming a tesselation array of simple computational array elements. Each element performs a simple logic function on several inputs. They are modelled as programmable lookup tables which constitute the array configuration. Interconnections are configured by programming to multiplex the logic gates. Logic functions and interconnection are defined by the on-chip RAM fuse cells which hold the configuration data rather than masking. The processing elements form large arrays of logic blocks that implement logic gate functions such as AND, NAND, OR, NOR and EX-OR linked by a grid of connections [Villasenov & Mangione-Smith 1997]. The configurable logic blocks are surrounded by vertical and horizontal routing channels. Logic cells are embedded in a general routing structure that allows arbitarary point-to-point connections. The logic blocks and the grid are configured to any logic gate in any pattern within ~10μs. Such programming capability gives a dramatic increase in functionality over ASICs. Coarse-grained FPGA's have a small number of sophisticated logic blocks while fine-grained FPGA's have alarge number of simple logic blocks. A single FPGA can perform a series of sequential tasks by dynamically reconfiguring itself between each task. FPGA's can be implemented with SRAM, EPROM, EEPROM or antifuses. Antifuse devices are one-time programmable. In the unblown state, the antifuse is an oxide-nitride-oxide dielectric that prevents current flow between the polysilicon electrode and the silicon substrate. Application of 16V across the dielectric melts the antifuse dielectric to provide a conduction channel. SRAM-based FPGA's are reprogrammed from ROM whenever it is powered up, so multiple configurations are possible. EEPROM/EPROM FPGA's retain configurations with power-down, and configurations can be altered electronically but they are inflexible. SRAM-based FPGA's are utilised in reprogrammable systems. SRAM is distributed throughout the FPGA logic block arrays on a one-to-one basis to transistors. Connecting 2^n program bits to a multiplexer enables any n-input boolean function to be implemented as lookup tables. On-chip RAM overcomes the problem of off-chip input/output latency. The volatility of static RAM allows hardware reconfiguration from multiple configurations held in ROM. There are two possible implementations of FPGA's [Hutchings & Wirthlin 1996]: compile-time reconfiguration which implements a single configuration per application or run-time configuration which implements multiple configurations per application. Compile time reconfiguration is the simplest mode resembling the ASIC approach to performance acceleration, but run-time reconfiguration is far more powerful and flexible. Run-time configuration allows rapid reprogramming on the fly during actual operation. This allows the preloading of multiple configurations and rapid switching between them at each clock cycle with efficient re-use of array elements through temporal multiplexing, ie. the same circuitry can be reused for different algorithms. Logic functions are implemented by programming the memory block with read-only patterns during configuration. Performance is limited only by SRAM block access times ~150 MHz today. FPGA's can dynamically alter the configuration to changing data sets. They offer greater computing capacity per unit area than conventional processors.

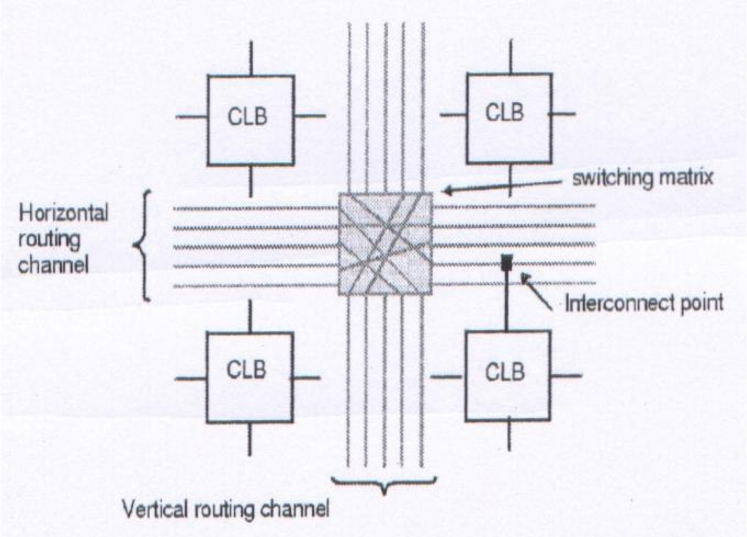


Fig 8-2 Internal structure of typical FPGA device

A typical FPGA is the Xilinx XC4000 series FPGA which has 400 logic blocks each with 4x256k SRAMs. It consists of RAM look-up table which is programmed with the truth table for combinatorial logic circuits. The interconnections are controlled by the contents of RAM. Each logic cell comprises of 3 lookup tables, two programmable flipflops and multiple programmable multiplexers. The lookup tables allow any logic function with 5 inputs to be implemented. The SRAM controlled multiplexers route the signals through the FPGA. FPGA's can implement array multiplication using its distributed RAM blocks as partial product lookup tables. Each connection can provide two 1.28 Gbps communication channels. FPGA's offer 10 times the performance advantage over high end general purpose workstations, ie. near ASIC-performance with the flexibility of reprogrammability. Multiple FPGA's may be combined into parallel processing architectures. They can be configured into multi-FPGA architectures such as mesh, systolic array, crossbar or hierarchical crossbars [Hauk 1997]. Linear arrangements are suited to sequential algorithms while matrix architectures are suited to multidimensional problems. SPLASH is a 40 MHz programmable crossbar array of 17 RAM-based Xilinx FGPA's each with 14 processing elements. It is capable of 300 MFLOPS performance. FGPA's can be used for logic emulation in the design and rapid prototyping of ASIC's. VHDL (Very high speed integrated circuit Hardware Description Language) is used to design FPGA logic. HDL models describe circuits through boolean expressions at different heirarchical levels from the gate level to the system level to the algorithm level. They provide specifications for the hardware circuits and their design [Dreike & McCoy 1997]. VHDL can model the behaviour and structure of electronic systems and test circuits' performance before their physical implementation. Libraries of common modules exist for re-use. The VHDL syntax is based on input-output specification and circuit function declarations and circuit descriptions. It is a dataflow language. FPGAs can represent 2D cellular automata with the field program acting as a gene with topological address and function coding. Each cell locally computes its coordinates as a function of its state and its environment (ie. its neighbouring cell coordinates). It can implement logical systems of array complexity as 2D cellular automata.

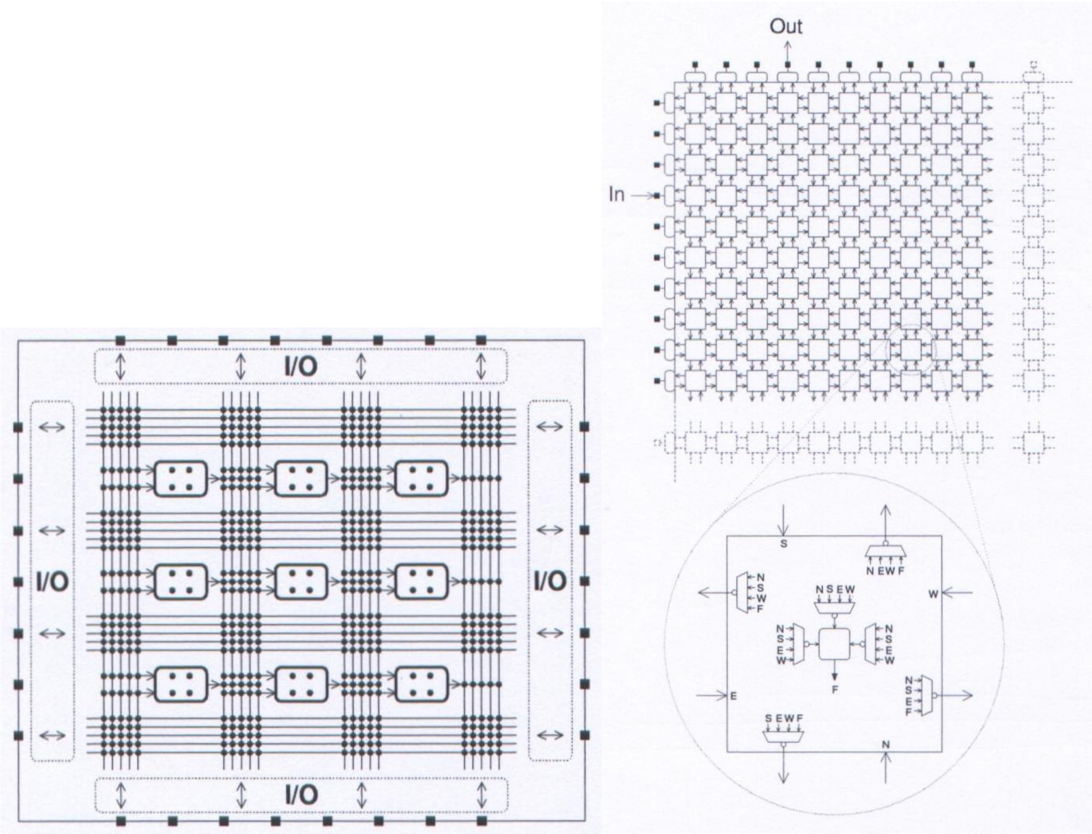


Fig 8-3 XC6216 FPGA [from Thompson 1996]

Algorithms based on biological analogies have become commonly adopted for solving difficult problems: genetic algorithms (and variants such as genetic programs and classifier systems which are not considered further) provide the basis for the evolutionary search of solutions to NP-hard problem spaces; and neural networks (highly simplified idealisations of neural architectures) provide the basis for the generation of non-linear functions for robust pattern recognition. Indeed, the use of genetic algorithms for the learning rule of neural networks have been successfully adopted. These methods are firmly rooted into control system applications in providing the "logic" of control problems. Increasingly, however, such techniques are being applied to hardware manifestations. The need for greater computational power onboard spacecraft has become a critical issue with the decade-long lag between terrestrial processors and space-rated processors. Multi-chip modules (MCM) are a step towards increasing the computational capabilities of spacecraft. Bio-inspired hardware is primarily confined to electronic rather than structural hardware in using genetic algorithms to evolve field programmable gate array (FPGA) architectures to solve control logic problems. FPGAs with ASICs (application specific integration circuits) are becoming increasingly commonly used for dedicated computations in terrestrial systems and onboard spacecraft.

Both ASICs and FGPAs have been utilised for TT&C (tracking telemetry & command) core functions for ESA's TEAMSAT housed in its OBDH (onboard data handling) box [Habinc et al 1983]. The OBDH box had a mass of 3.2 kg and a power requirement of 7 W and contained a TC board and TM board. ESA's radiation hard ASICs are silicon-on-sapphire chips with a mass of 15g for PSK modem functions and RS (Reed-Solomon) convolution encoding/decoding functions. Obvious applications for FGPA's include rapid pattern matching by comparing input patterns to large numbers of stored templates by reconfiguring itself for each data set [Hauck 1997]. FPGA's have also been used to implement Data Encryption Standard (DES) codes utilising 56 bit long encryption keys to encrypt 64 bit data blocks. A set of permutations translates the 56 bit key into 16 subkeys. The FPGA can reconfigure itself to compute each subkey. The chief disadvantage of FPGA's is their lack of on-chip memory to store intermediate results of computations. Data transfers between the FPGA and external memory slows computations down significantly but FPGAs with large memory holding multiple configurations are under development. Mirchandani & Figueiredo (1998) have suggested that FPGA parallel processing architectures would be suitable for TT&C gateways to translate between different retrieval protocols such as science data and housekeeping data at high data rates ≥150 Mbps. Whereas general purpose microprocessors are well-suited to irregular tasks with a large number of distinct operations, FPGA's are suited to regular tasks which involve a limited number of operations repeatedly. Hybrid architectures involve utilising FPGA's as coprocessors coupled to conventional microprocessors – 90% of computation time is spent on 10% of code in most programs.

8.3. EVOLVABLE HARDWARE

Evolvable hardware integrates reconfigurable electronics with genetic learning techniques [Zebulum et al 1997]. A circuit is represented by a binary string (genotype) which represent the circuit connections, components, etc.An initial population of strings is generated at random and evaluated according to how well the circuit performs the desired function (codified as a fitness function). FPGAs are two dimensional arrays of reconfigurable logic blocks with reconfigurable switches which determine how i/o blocks are connected. There are configuration switches within each block and there are i/o blocks around the periphery which interface to the chip's pins. The settings of the switches are stored in configuiration memory which can be written to in software. Thus the configuration memory defines the electronic circuit, yet also defines a computer program. The contents of configuration memory may be encoded as a genetic algorithm and subjected to evolution. Intrinsic methods involve evolution and evaluation occurring within the device whereby all solutions are downloaded to the device without the need for simulation. Extrinsic methods involve the use of software simulation models (eg. SPICE) for evolution and evaluation, the final solution being downloaded to the device. The problem with simulations is that they are limited in their fidelity in simulating of real world noise and physical characteristics of electronic circuits. Evolutionary hardware can generate electronic circuits that are beyond the scope of conventional methods [Thompson et al 1999]. Analogue circuitry offers the use of real time rather than clock pulses to sequence and synchronise signals. They are continuous time dynamical systems. The basic building blocks include amplifiers, filters, oscillators, voltage/current sources to build more complex circuits. The use of increasing length genotypes in evolutionary electronics was discussed by Zebulum et al (1997b) on the basis that evolved electronic circuits sizes are not generally known in advance – evolutionary algorithms should start searching at the most parsimonious solutions but the rate of genome growth should balance the faster, non-parsimonious and slower, parsimonious solutions. The fitness evalutation should penalise large genotypes.

An onboard robot controller was evolved for a two wheeled mobile robot with two time-of-flight sonars to display simple wall avoidance behaviour [Thompson 1996, 1997, Thompson et al 1996]. The conventional controller approach would be based on timers to measure the time of flight of the sonar signals which require signals to be synchronised. A finite state machine (which may be encoded as a look-up table in RAM) would output the appropriate signal for pulse width modulator to each motor. Relaxation of synchronisation allows dynamics to be exploited whereby raw sonar echo data is directly fed into the motors without processing using only 32 bits of direct-addressible RAM and three flip-flops – this represents a dynamic state machine (DSM) which includes an analogue temporal factor between asynchronous signals as opposed to a finite state machine approach. The 32 bits of RAM were encoded directly into a linear GA which used an elitist strategy which added mutations (bit-flips) to provide fault tolerance. A conventional design would require one or two orders of magnitude more Si area. This approach to robot control is fault tolerant [Thompson 1995b, 1996b].

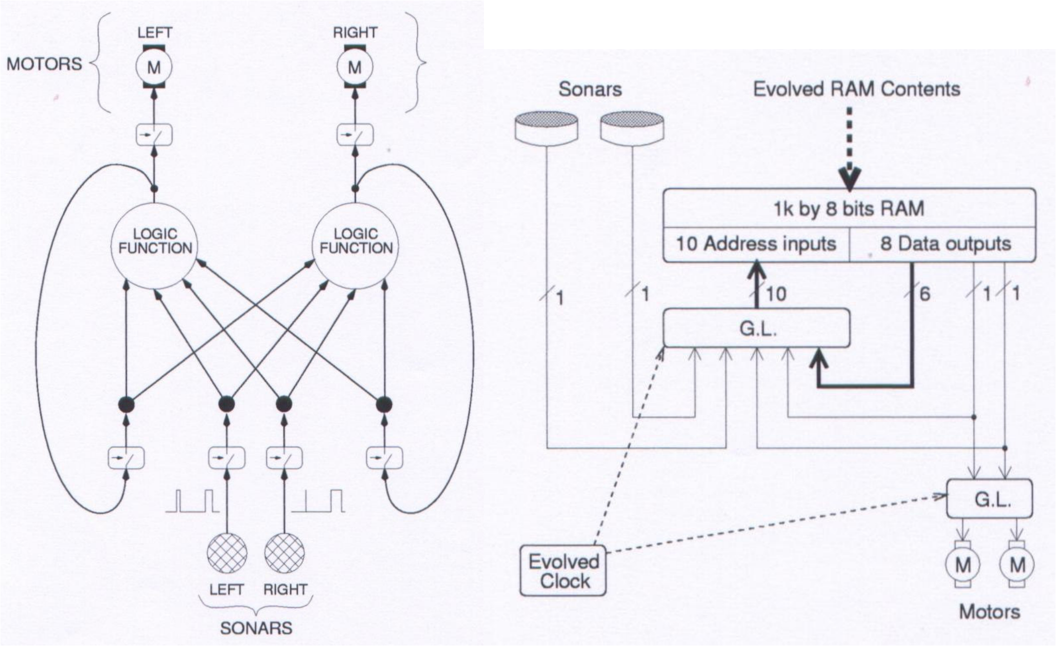


Fig 8-4 (a) Evolvable dynamic state machine (b) Hardware implementation of dynamic state machine [from Thompson et al 1996]

Similarly, an electronic oscillator circuit was evolved on the Xilinx XC6216 FPGA [Thompson 1996a,b]. This FPGA allows rapid downloading of configuration bits and can implement most two-input Boolean functions and many three-input Boolean functions. The 10x10 northwest corner of the 64x64 FPGA array was used. The NEWS (north east west south) inter-cell connections between the four neighbours of each cell were configured using multiplexer (four-input transistor) switches according to the contents in RAM memory throughout the chip. The FPGA cells can be configured to perform Boolean functions but real transistors are continuous, high gain asynchronous analogue devices which operate digitally by saturation. No clock was provided, so the FPGA acts as a continuous time, dynamic system. The periphery of the array interface to external input/output pins. The task was to discriminate between 1 kHz and 10 kHz square waves without the use of a clock or off-chip RC oscillators by outputting +5 V for one input and 0 V for the other – these frequencies are some five orders of magnitude greater than the ~1 ns gate delay times. For each cell, the 18 multiplexer control bits represented a linear bit string of a genetic algorithm, ie. 1800 bit genotype in total to configure the 10x10 array. The GA used was a population of 50 with cross-over probability of 0.7, mutation rate of 2.7 per genotype and elitist selection. The tone generator drove the circuit input with 5 x 500 ms bursts of 1 kHz and 10 kHz square waves each. The fitness function was: $F = \frac{1}{5}\left|\left(k_1 \sum_{t \in S_1} i_t\right) - \left(k_2 \sum_{t \in S_{10}} i_t\right)\right|$ which maximised the difference between the outputs when inputs were 1 kHz and 10 kHz respectively where k_1 and k_2 were calibration constants 1/30730.746 and 1/30527.973 respectively to yield zero fitness with outputs connected directly to inputs. The slow oscillations were obtained by generating beat frequencies from two close high frequency oscillations. The final circuit after 5220 generations yielded the required discrimination performance. However, most of the 1800 bits could be mutated without affecting the fitness of the circuit - the core of the evolved circuit comprised 32 of the 100 cells, ie. of 2^{1800} possible genotypes, around 2^{1200} represent valid designs which are rapidly converged upon due to searching along high fitness ridges within the genospace [Harvey & Thompson 1996]. These pathways – neutral networks – are traversed through single point mutations with no change in fitness. This indicates the incidence of "junk" coding. The mutation rate corresponds to one mutation per functional non-junk proportion of the genotype – the neutral network which percolates widely through the genotype. Replication of the evolved circuit using separate CMOS multiplexer chips did not work [Thompson & Layzell 1999]. The solution was found to be highly temperature sensitive outside of the $\pm 5^{o}$C experienced during evolution. Robustness must be imposed by the environmental conditions. Furthermore, porting to the solution to a different FPGA chip or even a different area on the same chip yielded degraded performance, eg. different frequency discrimination. The dc current gain parameter h_{FE} in transistors have variable values, eg. BC109 has a nominal value of 350 but in fact varies from 200-800. Evolved electronic circuits do not have clear functional decomposition into modular subsystems. They do however exploit the semiconductor physics of the FPGA to enable timing mechanisms to be implemented. The Evolvatron is an expandable collection of XC6216 FPGAs which are maintained under different conditions such as temperature, power supply voltages, output loads, fabricaton tolerances, device ageing, interface electronics, load conditions, and sub-array positions to provide selection pressure for robustness [Thompson 1998]. A solution circuit is downloaded to each FPGA and evaluated across the training regime provided by the Evolvatron. The evolvable motherboard is an approach which reduces reliance on FPGA devices and allows a variety of electronic components to be interconnected to each other [Layzell 1998a,b, 1999].

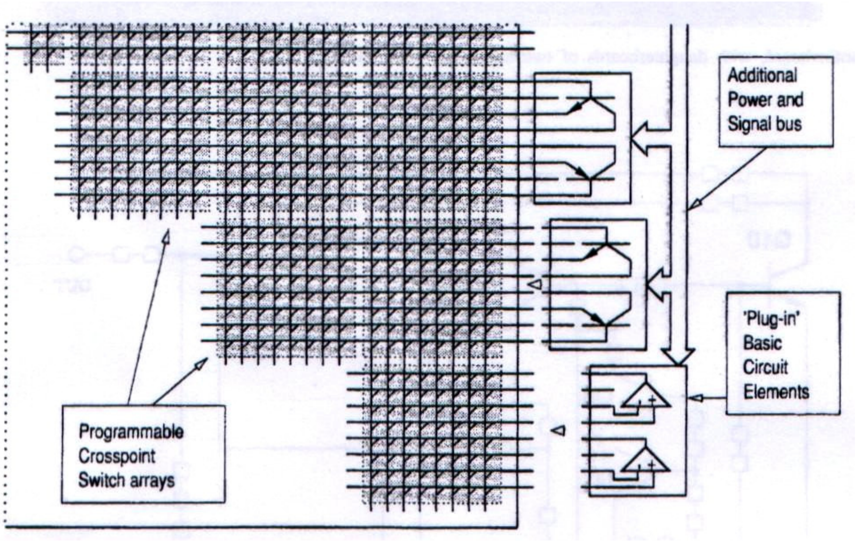


Fig 8-5 Evolvable motherboard [from Thompson et al 1999]

Candidate circuit designs are represented as an array of bit strings which specify component types, values and their interconnection. It comprises a diagonal matrix of analogue switches connected up to 6 plug-in daughterboards of transistors and operational amplifiers. Some 1500 analogue switches allow row/column interconnections with a search space of 10^{420} possible circuits. Its great advantage is that, unlike the FPGA, all its electronic components are accessible to measurement. One successful task was the evolution of a NOT gate using bipolar transistors. Another successful task was to evolve a transistor amplifier using GAs with a series of fitness functions depicting the desired dc transfer function of maximising the differential input voltage within a linear region flanked by saturation regions: $F = \max_{i=1}^{n-1} |V(i+1) - V(i)|$. The evolved circuit was unconventional – the input was applied to the collector (rather than base) of transistor Q1.

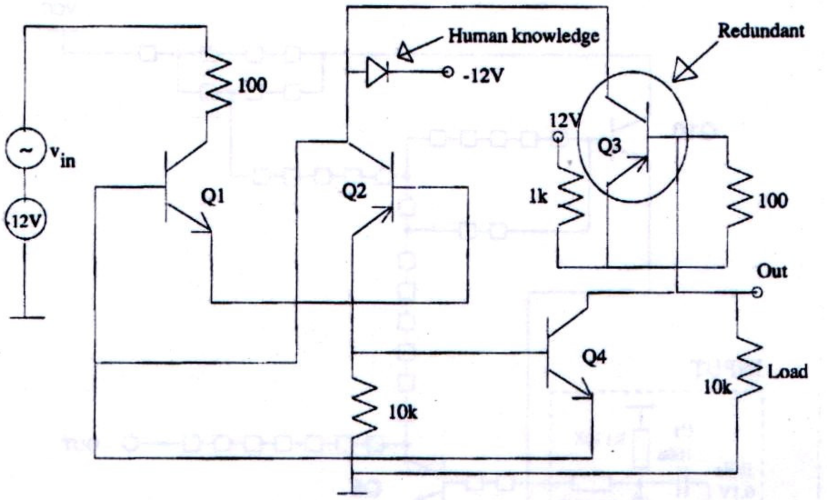
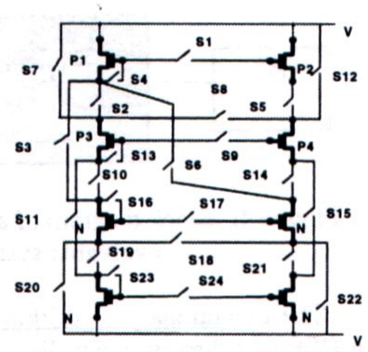
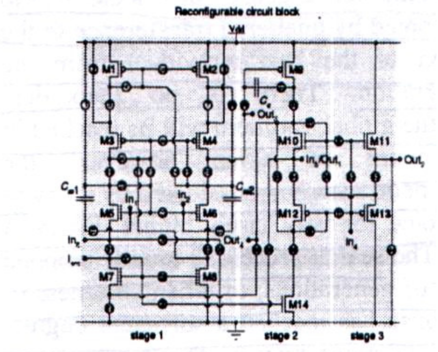


Fig 8-6 Best evolved amplifier [from Thompson et al 1999]

Transistors Q2 and Q4 acted as current amplifiers with transistor Q1 biassed in reverse region while Q3 was redundant. Genetic programming as a form of automated program synthesis has also been applied to hardware evolution in the generation of electrical circuits that perform a set of user-defined functions including a lowpass filter, a tri-state frequency discriminator, a mathematical computation circuit, a time-optimal robot controller, a sorting network and an amplifier [Koza et al 1998a,b]. Genetic programming essentially maps acyclic program trees to line-labelled cyclic graphs representing electrical circuits and their encoding resembles a developmental process.

The chief disadvantage of evolutionary hardware is that it exploits the physics of the electronic circuitry. This makes it unportable. However, it is conceivable that flight versions of electronic circuits may be evolved as one-off hardware components, though this could potentially cause problems in replicating circuit behaviours in flight spare components. Finally, the scalability of such techniques to more complex circuitry is an issue that has not been resolved – the longest genotype length used is 3500 bits while the entire surface of an X6216 FPGA requires 200,000 bits to code. We suggest that evolutionary hardware currently has limited application in spacecraft systems primarily due to its irreplicability. However, the advent of the field programmable transistor array (FPTA) provides the basis for analogue evolvable hardware necessary for interfacing to spacecraft sensors [Stoica et al 2002]. It has evolvable granularity to allow low-level granularity. Each cell contains 24 prgrammable switches and an array of 8 transistors capable of being configured as digital or analogue circuits. A more recent version, FPTA2 has 8x8 programmable cells, each cell comprising 14 transistors connected through 44 switches able to map different building blocks for analogue processing. The chip can receive 96 analogue/digital inputs and 64 analogue/digital outputs. Each cell is programmed through a 16 bit databus and 9 bit address bus. A total of 5000 bits is used to program the whole chip.





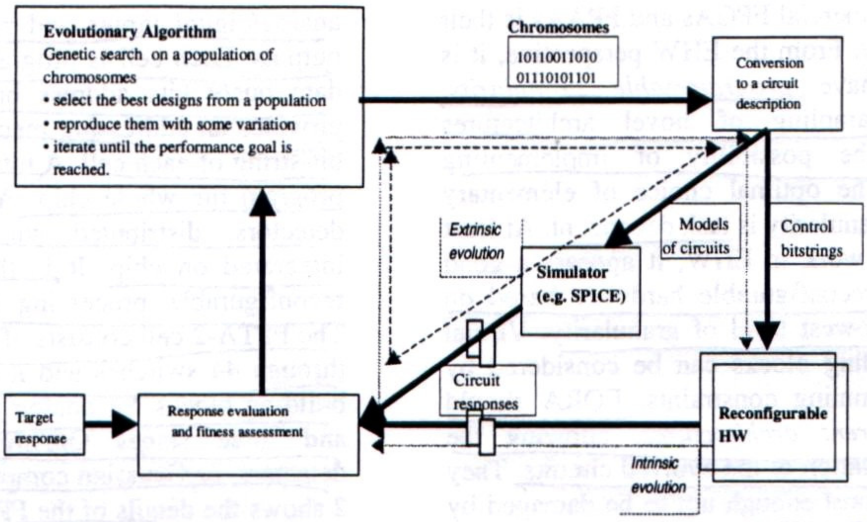


Fig 8-7 (a) FPTA cell topology: FPTA-0 and FPTA-2 chips; (b) main steps for evolutionary synthesis of electronic circuits [from Stoica et al 2002]

An array of 16x8 photodetectors are also distributed within the cells for sensing. The hardware is controlled through LabView. Genetic algorithms may be used to design circuits to perform specific functions such as analogue filters. The binary genetic code represents the status and topology of the switches. A population of chromosomes is randomly generated. Chromosomes are converted into circuit models (eg. SPICE) or programmable hardware for evaluation. Circuits responses are compared and ranked and a new population is generated from the best performing circuits. This is subjected to probabilistic selection followed by cross-over and mutation operations. This iterative process is continued until sufficiently effective solutions have been generated. New evolutionary cycles can re-configure the FTPA if ionising radiations, ageing, excessive temperatures generate faults or for new functionality. A half-wave rectifier has been successfully evolved from a population of 100 over 200 generations. An autonomous tunable filter was also evolved successfully. Self-repair of an analogue multiplier was also re-evolved using two cascaded FPTA cells connected by 6 switches, comprising 88 bits. ADCs for sensor processing have also been evolved with reconfigurability, eg. for a re-configurable antenna control system.

9. Ground Station & Human-Machine Interfacing

9.1. INTRODUCTION

The ground segment of a space mission is an important part of the spacecraft system. The ground system controls and monitors the spacecraft and its payload by transmitting command instructions and data using the received spacecraft telemetry and mission data. The ground station is responsible for the maintenance of the communications link and tracking functions and dealing with anomalies through workarounds. The key is the interface between the spacecraft and the ground station. In this section, we examine some human-computer interfacing that exploits biomimetic principles. Indeed, the trend in human-computer interfacing is to maximise the transparency between the human operator and the spacecraft – this is the principle behind virtual reality. We are attempting to create a unified system of the human operator meshed with the remote spacecraft despite the distance between the two. In effect, we are attempting to create a cyborg – a cybernetic organism. Indeed, the term cyborg was coined by Manfred Clynes and Nathan Kline in an article “Cyborgs and Space” in the *Astronautics* magazine in 1960. The article stressed the importance of closer integration of man and the machine and the natural development of artificial enhancement of the human being in order to function effectively in extraterrestrial environments.

9.2. VIRTUAL REALITY SYSTEMS

Virtual reality (VR) is a natural evolutionary development in man-machine interface based on realistic 3D computer graphics which aspire towards ultimate transparency between the computer and the human sensory-motor system. VR is the integration of computer graphics with the human sensor-control-actuation cycle to create the illusion of "telepresence" that the operator is physically present at the remote worksite in a computer generated environment through this transparency. It requires real-time feedback of a similar quality and form as that received by the eyes, ears and skin. It increases the situation awareness and reduces the operator's physical and mental workload. Indeed, telepresence projects human capabilities to remote locations. It allows the computer to simulate the particular 3D environment with dynamic objects controlled only in part by the human and allows human actions to be translated within that simulated world (cybernetic simulation or "cyberspace"). This cyberspace comprises the storage medium for all the interactive information accessible by the operator. Cyberspace in turn generates sensations to make the illusion of participation and interaction in that world. This property of immersion gives the observer the experience of reality rather than the mere observation of reality from outside. Real-time interactions between humans and machines through perception, feedback and control was required. For such real-time operation, a minimum of ~30 sensor readings/second are ideally required though lower rates ~10-15Hz have been used effectively. Indeed for delicate manipulation with tactile and force feedback, ~1000 samples/s may be required. As long as the feedback from the robot correlates with that expected by the simulator, the robot proceeds with its operation, but if the feedback is unexpected, the robot freezes until the operator determines the course of action.

Current implementations of virtual reality requires special headgear and special gloves. TV offers a severely reduced visual field in comparison with the human FOV of 50^{o} up, 80^{o} down, and 90^{o} sideways. Furthermore, a 2D representation of a 3D world is not the ideal representation. The helmet-mounted display is a spin-off from military aircraft cockpit headup displays and allows stereo pair imaging and telepresence [NASA Telerobotics Unit 1988]. The head-mounted display generates two stereoscopic images one for each eye of the 3D scene and allows head motion coupling. It detects the operator head motions and controls remote cameras accordingly to cover the simulated task environment. Three axis-aligned Helmholtz coils detect the head movements along the three rotational axes. Two viewfinders mounted onto the helmet each comprising of a CRT screen and converging lens give the operator a view of the scene. A computer-generated stereo picture pair is displayed onto the screens, one for each eye. Each eye is projected with a slightly offset view of the same image. Further depth information is provided by motion parallax through sensory feedback from head position. A lens forms a virtual image of the stereogram pair behind the display screen. With the correct geometric conditions, left and right images overlay to form a single 3D image. Lasers could be used to detect and track eye motion to produce a continuous virtual world. Such displays by spanning the visual field give the onberver the sense of immersion rather than looking in from outside. Stereo imaging gives the sensation of depth and gives faster task performance particularly for more complex tasks. A counterweight on the helmet provides balance for the helmet. Such perspective and 3D displays of simulated environments are computationally intensive and should be performed at the ground station using transputer technology. The chief disadvantage of head-mounted displays are that they are tiring for the eyes, are heavy causing neckache and can induce nausea.

Data gloves allow tactile and force feedback to be incorporated. The virtual hand representation is slaved to the finger and hand sensors of the data glove. Fibre optic cables between the layers of cloth run along each finger. An LED at the wrist sends light down the cables to phototransistors at each of the finger ends and measure the bending of the fingers. Alternatively, piezoelectric materials may be used as strain guages. Both the helmet and the gloves are studded with position and orientation sensors to allow the head and hands to be referenced to point in the 3D graphical cyberspace. For complete VR immersion, a body suit which senses the orientation of the operator's arms and legs within the 3D space may be used. Exoskeletons may be adorned which allow or resist any movement of the body through feedback from the computer. Further developments have incorporated a virtual workstation where specified hand signals generate a graphic control console to appear within the internal world allowing the operator to issue commands without exitting from the virtual world. The critical requirement is to maximise the transparency of the man-machine interface by tight coupling through the removal of the distinction between the system and the user's environment.

Caldwell et al (1994) succeeded in replicating the 4 basic human skin sensations of pressure, texture, temperature and pain. Force sensing provided information on pressure for shape and hardness determination, piezoelectric dynamic vibration sensors provided information on texture and slip, while fast response thermocouples provided information on thermal conductivity. Pain was recorded as an overload in all three sensors. Feedback was provided through an operator's glove and sleeve. Thermal feedback was provided through a Peltier effect heat pump, texture/slip and pressure feedback was provided by increasing temperatures towards the thermal design limit of 50°C. The system revealed that operators gave 90% correct identification of surfaces after only 10 minutes of training.

9.3. AUTOMATED SPEECH RECOGNITION

Speech recognition is one mode of communication that is presently being developed to enhance man-machine interfaces. Speech recognition systems match a transform of speech input to a set of stored representations. Speech is one of the fastest ways to communicate with the advantage that it leaves the hands and eyes free for other tasks and can be used in the absence of visual input [White

1976, 1990, Rudnicky et al 1994]. Consequently, this mode of communication is highly desirable for adaptive man-machine interfaces which adapt to the user rather than the user having to adapt to the interface, eg. in telerobotics [Norci & Stanley 1989]. Natural language as an information processing activity of great complexity is the most flexible form of dialogue between the user and the system (for the user). A natural language interface must be more robust than a command language. The computer system should be able to adapt to the user by compensating for weaknesses and offering help to decrease the user's mental and physical workload. Natural languages have the advantage over structured command languages in that no learning of special vocabulary or artificial command syntax is required for communicating with the system and the computer system itself transforms the natural language into a formal language for interpretation, ie. using a compiler/interpreter to associate a valid function template with natural language pattern input.

Natural language processing involves multiple processing tasks - phonetic analysis processes sounds, syntactic analysis examines how words combine to form sentences through grammatical rules, semantic analysis processes meaning of words for interpretation, and pragmatics is concerned with the contextual effects of language on agents. This is a hierarchical process. Natural language processing is similar to pattern recognition but is less well-defined and relies on statistical models of the regularities of syntax of the language. The essential requirement for realistic automatic speech recognition is to translate acoustic information into computer language commands.

Speech is produced in the vocal tract which may be modelled as a resonating cylinder open at one end which emits variable amplitude and frequency. Manipulation of this airstream by the larynx and the tongue provide the basis for distinguishing vowels and consonants. Information is encoded in the temporal patterns of the sound. The initial stage in speech recognition is the use of transducers to convert sound waves into an electric signal. Speech processing signals are typically filtered in the bandwidth 100-3200 Hz and then digitised at 16 kHz. Frames are constructed ~20 ms in length separated by 10 ms. The measured acoustic pattern represented as spectral properties is then matched against internal spectral models stored in memory, eg. word templates and/or sets of grammatical rules. This matching is usually a Markov process. The hidden Markov model is a finite set of states each associated with a probability distribution. English would require some 1000 mapping rules to cope with pronunciation variations. All speech sounds may be represented as a linear superposition of sine waves of different phases. Consonants in speech carry most of the intelligibility while vowels possess most of the energy as they tend to be louder. Consonants also tend to be at higher frequencies than vowels by virtue of the constriction of the airstream. The most and least intense speech sounds can differ by as much as 50 dB. A power spectrum analyser (equivalent to the cochlea) processes the signal by measuring the relative intensities of each component sine wave (since phase is used for direction-finding rather than providing acoustic information). This provides the parametric reformulation of the speech sounds. Speech is a wideband signal (particularly in the 1-3kHz range) modulated in three ways: (i) vocal cord frequency; (ii) pitch duration; and (iii) frequency modulation of the sound spectrum. Speech may contain redundant information which may be removed through data compression to reduce the computational load. One technique of data compression is formant tracking whereby formants are acoustic waveforms generated by the human vocal system: the major peaks in the multi-harmonic power spectrum (formances) are produced in the vocal cavity as resonances and most of the information content in speech is contained in three principal formants and these can be interpolated. Consonant/vowel combinations contain the most rapid formant transitions. These are the acoustic cues which mark specific phonetic features - second and third formant transitions are the acoustic cues to the position of articulation of the initial plosives. The speech amplitude spectrum over time contains peaks and valleys. Such fluctuations arise from the response of the vocal tract to excitation. Vowels have the greatest amplitude forming the core of syllables whereas amplitude is minimal ~15 dB in the consonant region between vowels due to restriction of the vocal tract. Each contrast produced by consonants give a number of different patterns of spectral shape as a major cue to vowel identity. The identification functions for consonant contrasts are S-shaped with a steep gradient at the boundary point indicating that perception divides the acoustic continuum for discrimination. Amplitude variations occur at the syllabic rate of 200-300ms (dominated by vowel duration). Stop consonants (p, t, k, d, d, g) and nasal consonants (m, n) exhibit rapid spectrum changes over 10-30 ms due to abrupt vocal tract changes though nasal consonants have greater low fequency energy and lower higher frequency energy than stop consonants. The evolution over time of the formant patterns are tracked for frequency, pitch and amplitude to give all the information necessary for regenerating speech with compression. A major problem is in the recognition of a set of words of a large predefined vocabulary (more than 1000 words) in unconstrained speech independent of the speaker. The speech input is continuous but the words are discrete and their boundaries are difficult to delineate. Content words (nouns, verbs, adjectives, adverbs) are often emphasised but function words (articles, prepositions, pronouns, etc) are often poorly articulated. Function words comprise only 4% of the vocabulary but comprise arouns 30% of speech by frequency. The approach used most commonly is hidden Markov models which utilise a parametric statistical approach. The input signal is modelled as a sequence of vocabulary words witgh a background signal. The background signal includes extraneous speech which the hidden Markov model represents. Another technique for data compression that is popular is linear predictive coding (LPC), a form of Wiener autocorrelation filtering. It represents speech in highly compressed form and is computationally efficient. It imposes a model of a linear acoustic tube on speech with cross-sectional area and length determined by the LPC coefficients. By normalising random speakers' characteristic tube length and cross-section to standard values, some small measure of speaker independence can be achieved.

Next, the parametric representation is grouped into words for matching against the word prototypes. Words are typically ~10ms long. These segments are compared with corresponding segments in word prototypes defined by their average pass band energies. A Euclidean or Hamming distance function is used as the similarity measure: the shorter the geometric distance in n-dimensional space, the greater the similarity. Linear predictive residuals may be used as another similarity measure such that the residual is the error between the LP filter to the speech form. Using word prototypes is inefficient, so words are represented as sequences of smaller phonemes as the basic unit. These represent syllables which form the digital units of sound composition into words, phrases, sentences, etc. Phonemes reduce the number of prototypes which need to be processed and reduces the memory requirement for word prototypes. Next morphological analysis distinguishes the word, its present participle root and its derived inflected form (eg. study-ing) and reduces the number of lexical entries in the stored dictionary. The morpheme is the basic unit that carries meaning. Phonemes are strongly affected by neighbouring phonemes causing difficulties in phoneme recognition. Triphone models take into account neighbouring phonemes. Phonological rules that describe legal phoneme sequences provide some relief from this. The process then continues from words to higher hierarachical patterns. The recognition process must be performed at many heirarchical levels in interactive fashion using hypothesise-and-test methods to overcome many ambiguities. Models are required at all levels with lower level models calling on higher models to resolve local ambiguities through high level expectations. Words are characterised by acting as single discrete units which are meaningful on a stand-alone basis. They are searated by pauses and cannot be embedded within each other. The output of the morphological analysis is a sequence of words.

The next stage is semantic analysis which requires inferencing procedures. Stanford Research Institute have developed a system called TDUS (Task-oriented Dialogue Understanding System) for communicating with a human about repairs on electromechanical equipment [Hendrix & Sacerdoti 1982]. Information about the repairs was recorded in procedural network data structures. The network divides tasks into a number of subtasks such that each action is associated with a number of subactions which are partially ordered. The structure of the task oriented dialogue closely follows the division of the task in the network into increasing detail of subactions. Furthermore, referential expressions refer to objects in the current or higher subtasks rather than sibling subtasks, ie. referential expression in natural language follow similar conventions to variable references in block-structural programming languages though not explicitly:

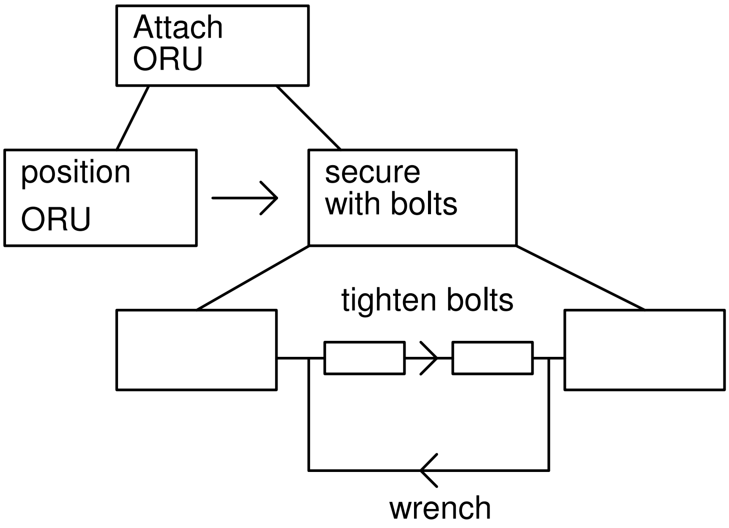


Fig 9-1 Task-Oriented Dialogue Understanding System (adapted from Hendrix & Sacerdoti 1982)

Many automatic speech recognition (ASR) systems require careful pronunciation of a limited number of words <1000 from a small set of known speakers and require ~0.1s pauses between words to isolate them. Some ASRs however are capable of continuous speech recognition, but again have limited vocabulary <100 words and a small set of speakers. Generally, isolated word recognition systems have larger vocabularies than continuous systems. Many of these systems can give word recognition accuracies >90% for vocabularies of a few hundred words. Commercial standards require a word error rate <5% which is still some 5 times greater than for natural speech error rate (~0.8%). Some ASR systems can have vocabularies up to 10,000+ but only under optimal conditions. Speaker-adaptive systems are initially speaker independent but which are modified to become speaker dependent. However, ASR is computationally expensive. The need is for increases in data dictionary compression and directed dictionary retrieval to reduce the recognition time. Hearsay-II speech recognition and language understanding system is a blackboard system that integrates information from multiple independent knowledge bases and employs hypothesise-and-test paradigms such that phoneme strings predicted by top down analysis are compared to strings of phonemes produced by acoustic bottom up analysis. Arbib & Caplan (1979) provided the conceptual framework for Hearsay II:

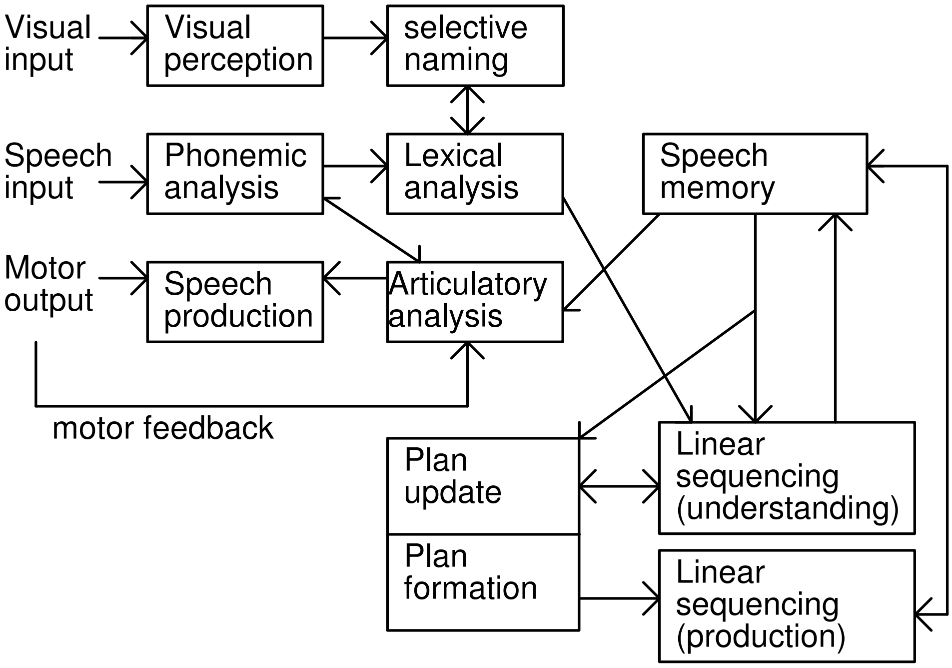


Fig 9-2 Hearsay II blackboard (from Arbib & Caplan 1979)

Each linguistic task is performed by several functional knowledge-based components both in parallel and in sequence. Because the knowledge sources act in parallel, they exchange results through the common blackboard memory to provide ccoperative computation. This provides a means of interconnecting different sources of knowledge. Hearsay II provided different levels of representation with each knowledge source representing a different functional module of the human brain. The blackboeard linking the knowledge sources represented working memory. Solutions were found by iterative hypothesise-and-test processes. Natural language understanding should follow ASR to achieve recognition of continuous speech because continuous speech is filled with ambiguity which can only be resolved with additional semantic knowledge - this is language understanding as opposed to speech recognition.

9.4. NEURO-ELECTRONIC INTERFACING

The ultimate man-machine interface is a hands-free thought-controlled computer based on neural-electronic linkages [Lusted & Knapp 1996]. Neurotrophic chemicals which encourage nerve growth can be exploited to grow nerves attached to metal electrodes. To avoid attack by the immune system, silicon may be coated with specialised molecules to attach to the Si surface at one end with the other end allowing nerve growth factors to allow the growth of neural axons and dendrites. Photolithographic methods can etch the nerve growth factors like microelectronic circuits. Microprobe electrodes can record signals from peripheral nerves. Cochlear implants are a well-established technology which detect a limited range of sounds including speech. Cochlear implant electrodes follow the cochlear spiral for around one and a half turns. Only 15-30% of the neuronal population of auditory cells must be intact for the cochlear implant to allow speech recognition. Cochlear implants bypass damaged hair cells by stimulating the auditory neurons directly. A microphone and speecg processor are worn externally. The speech processor analyses sound in terms of frequency and amplitude. Cochlear implants involve implantation of electrodes into the cochlea to simulate the auditory nerve wired to a radio receiver which picks up transmissions from a sound analyser. Sound is decomposed into frequency bands and distributed accordingly along the electrode array. Each channel responds to different sound frequencies to stimulate different part of the auditory nerve. A 25 mm long 320-640 μm wide micromachined Si electrode array as the basis of a cochlear implant was developed [Bell et al 1998]. Cochlear implants are surgically embedded within the inner ear and send electronic signals to the auditory nerve. There are around 3500 hair cells within the cochlea planted along the basilar membrane at the base of the cochlea which responds to mechanical vibrations. The cochlea's outer hair cells amplify the motion of the basilar membrane. The movement of the basilar membrane triggers movement of the inner hair cells. High frequency sounds travel a shorter distance than low frequency sounds in the cochlea. The implant comprises an external microphone and a speech processor behind the ear. A receiver is implanted within the ear and connected to the cochlea by eight electrodes. Sounds are detected by the microphone and sent to the speech processor which transmits the signal as radio waves to the receiver. The receiver transmits electric pulse signals to the cochlea which stimulates the auditory nerve. The MIT silicon cochlea implant is more strongly biological in that it emulates the travelling wave function of the basilar membrane. Such methods offer the potential for electronic ocular implants comprising of photoreceptor imaging array sensor with analogue conditioning to emulate the retina prior to signal processing in the optic nerve. Such technologies have vast applications in neuromuscular prosthetics and telerobotics. Many injuries of the human sensory system are due to defects in the sensory organs themselves, eg. blindness is often due to damage to the eyes rather than the visual cortex. Direct stimulation of the visual cortex in such patients evoke phosphenes – the perception of points of light in the visual field. Needle electrodes implanted directly in the brain could theoretically transmit images or text to the brain as electrical impulses, stimulating neurons in the visual cortex. Electrical activity recordings from arrays of thalamic nerve cells behind the optic nerve have been subjected to "linear decoding" to extract visual images of light/dark contrasts. Visual prosthetics may be implanted anywhere along the visual pathway. Electrodes may be placed on the retina or subretinally. The Harvard/MIT retinal implant captures visual images from a small CCD camera mounted onto a pair of spectacles. These images are transmitted to a microchip embedded with the spectacles. The electronic signal is projected by laser beam through the eye to a stimulator chip mounted onto the retinal surface. The stimulator chip converts the laser data into an electronic signal which is transmitted to the ganglion cells which connects to the cone and rod cells and onto the optic nerve. The Artificial Silicon Retina (ASR) is a microchip of some 3500 solar cells, each of which contacts retinal cells. The solar cells convert light into electrical signals which stimulate the retinal cells. There is no reason why the solar cells may not be made sensitive to ultraviolet or infrared light. Virtual Retinal Display (VRD) uses 3 red, green, blue laser scanner mounted over the eye to project colour images through the cornea to the retina, with the laser beam moved by a pair of mirrors to project pixels sequentially at 10^6 Hz. Each frame of 1000x1000 pixels is redrawn at 60 Hz. Infrared detectors must monitor the eye movement to control the image's shift across the retina. However, such techniques are highly embryonic and are not really applicable directly to telerobotics. More indirect methods however suggest themselves. Silver chloride electrodes connected to electronic amplifiers can be used to measure voltages from electromyographic (EMG) impulses in the muscles through the skin during muscular contraction. The electronic amplifiers amplify these EMG signals by $\sim 10^5$ which are then digitised. Analysis of these signals allows the determination of which muscle fibres are contracting and by what degree. Functional electrical stimulation of muscles by surgically implanted electrodes in the spine can simulate control signals from the brain. The firing rate of neurons are directly related to the magnitude of contraction in muscle fibre innervated by the neuronal group. Electrical impulses ~10-100μV with a current of 4-20mA and a duration of 200μs at 12-15 Hz can innervate muscles through coordination is at present a major difficulty as neurons often innervate multiple muscle groups. Hence, muscle activity can direct the operation of a computer, eg. a hands-free means to adjust the position of a cursor on a computer screen. The eye exhibits a corneal-retina potential difference due to the retina's high metabolic activity. Electrodes near to the eyes can detect voltage fluctuations on the face when the eyes move. These electro-oculographic (EOG) signals can be used to indicate the direction of gaze and so move a cursor on a computer screen. A visual keyboard could be used to operate keys on the screen through this method. The human cerebral cortex produces voltage fluctuations on the scalp – the electro-encephalogram (EEG). They result from the pyramidal nerve cells of the cortex which act as current dipoles. However, unlike EOG and EMG signals, the EEG signals are not easily controlled as they are highly non-specific in origin. They are of several types: alpha-waves at 8-13 Hz occur when resting with minimal sensory stimulation; beta-waves at 14-30 Hz indicate alertness and mental activity; theta-waves at 4-7 Hz arise from emotional stress; delta-waves at less than 3.5 Hz are characteristic of deep sleep; mu-waves are associated with activity of the motor cortex. Since voluntary control is possible over alpha and mu waves, it is potentially possible to control a computer through this medium, but it is limited in scope. Evoked potentials which arise when stimuli are presented such as sound, light, etc offer an additional medium of control but suffer from similar deficiencies as EEG signals. It is unlikely that these techniques will be utilised in telerobotics in the near future.

Neural prostheses offer the possibility of hybrid human-machine symbiosis through fully implantable interfaces adapted from functional neuromuscular stimulation used in patients with transacted spinal cords of 5th or 6th cervical vertebra – such patients can move their shoulders and elbows but cannot use their hands [Heetderks & Hambrecht 1988]. Long tract neurons connect sensors and motor systems in the central nervous system – the most appropriate interconnection substitute in neural prostheses are insulated multiconductor wire micro-cables. However, they are subject to corrosive potentials within the body, so conducting polymers appear to offer a more useful technology. Other possibilities include ultrasound, radiofrequency and light interconnections. Hermetic sealing may be achieved through Ti, glass (SiO_2) and metal films but these are bulky – barrier coating with impervious material (to water and Na+ ions) is a thin film version. For recording electrodes, large surface areas are required to minimise electrode thermal noise – amplifiers and multiplexers provide multiple channels. For recording from intact biological sensors such as force, touch, position and touch require the ability to continuously record small populations of cells within a peripheral nerve. Signal processing of such multivariate inputs is in its infancy. However, placing electrodes more centrally such as in the dorsal roots might overcome some of these problems. Bypassing biological sensors with artificial sensors might be the more immediately available technology. Electrical stimulation of nerve or muscle requires depolarisation of the transmembrane potential below a threshold level by short cathode current pulses for $\sim 10^2$ μs. Nerve fibres require currents ~10-20 μA while muscle cells require currents ~15 mA. Micro-electrodes have smaller surface area require up to 50 A/cm^2 due to their higher charge density requirements for stimulation. Micro-electrodes of activated iridium offer higher charge densities than the more traditional platinum. Cardiac pacemakers are a well established technology for muscular stimulation but functional neuromuscular stimulation requires control to initiate and coordinate movement. External joint movement of the opposing shoulder can be used through functional neuromuscular stimulation to control grasp of the opposite paralysed hand which normally requires voluntary control. Implantable joint angle transducer can be used to achieve a similar effect. Cochlear implants are a well-established reliable technique which does not require complex control systems. The cochlear implant detects sounds from a microphone which are converted into electrical signals stimulate the cochlear nerve directly. Cochlear implants are only useful for functional auditory nerves – more central auditory prosthetics are a possibility,eg. the cochlear nucleus in the brainstem. A pair of bipolar platinum plate electrodes placed over the cochlear nucleus have yielded similar performance to cochlear implants. The addition of a multichannel speech processor would enhance the performance further.

The culmination of neural-computer interfaces, new robotic sensory modalities, electronic memory and processor brain extension, and robotic actuation to human performance is *Homo cyber sapiens* [Steels 1995]. A population of 50,000 neurons from the brain of a rat has been trained to fly a flight simulator controlled through electrical pulses to an array of 60 electrodes. Such developments, driven by ecological pressures of increased social complexity, could lead to a new species of embodied robots capable of sensing and acting in the real world as independent intelligent agents – *Robot hominidus intelligens*. Such a species would be modelled on biological systems as autonomous machines which maintain themselves capable of surviving in the real world environment.

10. Spacecraft Structural and Mechanical Systems

10.1. INTRODUCTION

A spacecraft is coupled to a hostile and highly variant physical world. Spacecraft structural materials are required to survive hostile conditions yet provide high levels of structural integrity and preferably adaptability to variable conditions. The structural system of a satellite is the structure of a satellite that supports all systems during the phases of the mission and it is completely dependant of the requirements of the entire system. The major mechanical parts are the launcher interface which connects the spacecraft to the rocket, the main thrust structure which absorbs the bulk of the mechanical forces during launch period, the secondary structural parts which connect the modules to the main structure, some miscellaneous parts and the payload modules. There are some structural requirements which must be considered prior to the design of the spacecraft. The structural loads, the resonant frequencies, the handling, the integration and the accessibility of the sub-systems need be taken into consideration. The stresses and strains applied to the materials during launch period and during high temperature changes need also to be calculated. With mathematical models and using the properties of each individual material used we can calculate the behaviour and strength of each material and hence the behaviour of our entire structure. Having no atmospheric drag it is possible to create satellites with various shapes. For example the satellites can be in a form of a box, a cylinder or even more complicated shapes. For geosynchronous satellites the most common shape is box and cylindrical; the cylindrical for spinning applications and the box shape for the non-spinning spacecrafts.

There are three types of spacecrafts. With three axis stabilising system, of a spinner type and of hybrid type which use partially de-spun and three axis stabilised with momentum bias. The first type of spacecrafts corresponds to usually large with extensive solar arrays, like the typical box-shaped GEO communication satellites. The spinning spacecrafts spin continuously and that rotation gives them small angular momentum with minor cross couplings. The hybrid satellites are a mixture of the above.

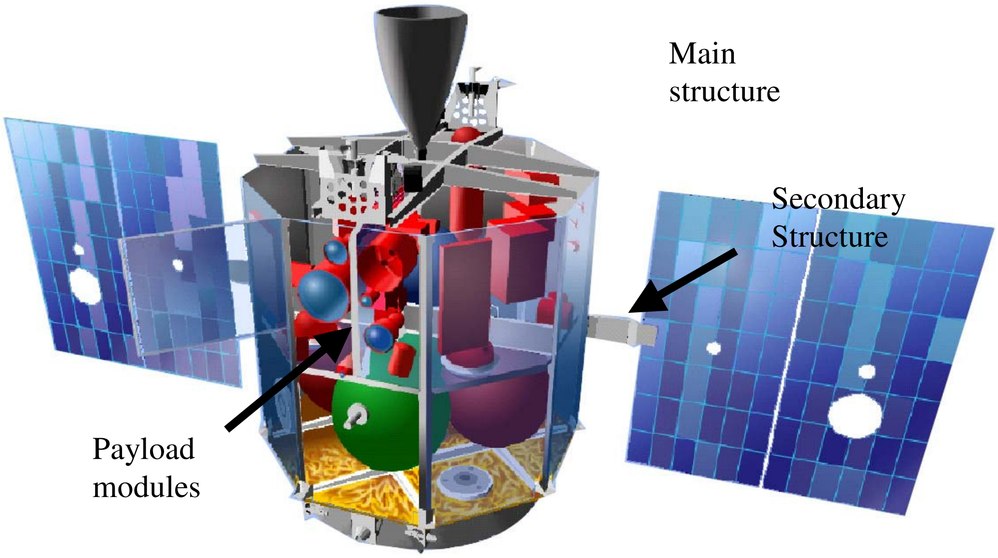


Fig 10-1 Structure of the Clementine satellite

In figure 4 the internal view of the Clementine spacecraft structure is shown. The battery packs, the sensors, and the reaction wheels are clearly displayed. Each satellite according to its type, application and size has a different design. Microsatellites developed in SSTL use the technology of modular blocks assembled in stack one on top of the other creating a very robust main structure.

10.2. SMART STRUCTURES

Smart or adaptive materials offer the potential for adaptive structures for manipulator actuation, antenna reflector profiles, active noise and vibration control of structures and in-orbit spacecraft health monitoring, eg. piezoceramic transducers for active vibration suppression or piezoelectric transducers for surface shape control. Vibration control can be accomplished by stiffening or damping the structure through the generation of internal forces to force the system towards stability. Smart materials are modelled on biological systems with sensors acting as a perceptual processing system, actuators acting like muscles and real-time microprocessor based control system acting like a nervous system [Vincent 1992]. Smart materials are materials that perform functions dependent on environmental changes. The sensors and actuators are embedded in the material during fabrication as an integral part of the structure.

Sensors that may be embedded into the composite material during manufacture may be optical waveguides or microelectronic devices of which fibre optic systems appear to be the most promising due to their capability to withstand the strains of the materials manufacturing process. They offer the possibility of distributed continuous monitoring of the interior of the composite at all stages of the structure's life as they are stretched or compressed, ie. structures with optical fibres. They can also serve to reinforce the composite. Coatings must be temperature resistant, eg. polyimide is stable up to 200^{O}C. Fibre optic sensors can detect a range of physical parameters through distortion of the propagation path of the optical signal: temperature, strain, pressure, electric and magnetic fields by the interaction of the parameter to produce a modulation of amplitude, phase or polarisation of a transmitted signal. Interferometric phase sensors detect the influence of physical parameters on the phase of coherent laser light in a single mode fibre with respect to reference arm fibres. The sensed information is integrated strain and temperature information. Phase shifts are caused by a change in the strain and temperature state in the fibre and may be detected as fringe shifts in an interferometric pattern. If a fibre is operated at a wavelength less than the cut off wavelength the fibre may be used as a modal interferometer to detect intensity changes due to strain or temperature variations. Polarimetric sensors in a fibre can also be used to detect strain/temperature changes. By incorporating elliptical cores orthogonal polarisation modes will propagate at different velocities generating a phase difference as a function of strain and/or temperature. Dual core optical fibres operating at two different wavelengths offer the possibility of separating strain and temperature information. To make measurements as a function of position along the fibre length the fibre is sensitised at discrete points along the length to create larger signals from each sensing element by for example Bragg reflection or partially reflective splices. One molecule thick Langmuir-Blodgett films such as organic dyes may be doped with rare metal ions to create light emitting layers. By changing the film thickness or molecular orientations the optical properties such as wavelength of light transmission can be altered.

Shape memory alloys may be embedded as 200-400μ plastically elongated wires or springs constrained from recovering their normal memorised length during fabrication. If the fibres are heated for instance by a current, they will generate a uniformly distributed shear load along the fibre to alter the material's modal response and elastic stiffness or if offset from the structure's central axis the structure will deform. Such systems could be used to control vibrations in large composite structures such as space platforms. The fibres may be arranged such that they induce a state of strain and the structure thereby altering the structure's stiffness, natural frequency and modal responses. Other possibilities include latch release mechanisms, fibre optic switching, microvalves of thin film NiTi on etched silicon. Electrorheological (ER) fluids may be used as actuators due to their reversible phase change in material characteristics especially bulk viscosity and flow rate when subjected to electrostatic potentials. The energy dissipation characteristics are thereby altered and the natural frequencies and resonance responses can be changed to damp out vibrations in composite structures by controlling the voltage imposed on the material. ER fluid voids in advanced composites offer this capability. Other possibilities include gear transmission without moving parts, shock absorbers and hydraulic actuators. Both SMA and ERF are sensitive to temperature and require tightly controlled temperature regimes in order to function, making them less useful for space application. Magnetorheological fluids (most commonly), foams and elastomers have rheological properties controllable by externally applied magnetic fields resulting from polarisation induced in suspended particles (10^{-5} –10^{-7} m sized particles of highly magnetisable material such as Fe with high saturisation magnetisation J_s=2.1 and volume fraction of 0.1-0.5 within synthetic oils or polar liquids) which causes the particles to form columnar structures [Carlson & Jolly 2000]. They may be described as Bingham plastics with variable yield strength such that the material shearing stress is given by:

$\tau = \tau_y + \eta\dot{\gamma}$ for $\tau>\tau_y$ where τ_y=yield stress

η=Bingham viscosity
$\dot{\gamma}$=shearing rate

$\tau = G\gamma$ for $\tau<\tau_y$ where G=complex material modulus

They are stable in the range –40°C – 150°C, require ~2-50W of input power, and have high specific gravity de to their high Fe content. They often used for torque transfer in brakes and clutches and dampers for vibration control. Electrostrictive and magnetostrictive materials appear to give enhanced performance for active damping over piezoelectric materials. Magnetostrictive material such as Terfenol-D ($Dy_{0.7}Tb_{0.3}Fe_{1.95}$) generates strains of ~1200 ppm, has high load bearing capacity, high compressional strength, high durability and low voltage requirements. Piezoceramics have also been demonstrated on micro-robots with piezoceramic legs – a femur provides vertical motion while the tibia provides horizontal motion. Electrorheological fluids and piezoelectric materials exhibit more continuous behaviour than shape memory alloys which tend to exhibit discrete behaviour. Changes in material properties may be effected according to [Thompson et al 1992]:

$M\ddot{x} + C\dot{x} + Kx = Q$ where x=displacement

Q=load
M(t)=mass distribution
K(t)=stiffness
C(t)=energy dissipation

These parameters may be varied to alter the structural properties for active damping by controlling vibration amplitudes, natural resonance frequencies, mode shapes, etc.

Electrorheological micromotors have been developed for the control of microfluidic actuators comprising capacitor elements to confine a flow channel of 10-20 mm in length exploiting the high power capabilities of hydraulics at microscales – electrorheological fluids can be used to control fluidic forces using direct electrical signals without moving parts (but ERF require high voltages) [Kohl 2000].

Metallic glass is a metal alloy with a chaotic structure unlike a normal metal alloy where the atoms are arranged in ordered crystalline form though it is not liquid [Zandonella 2005]. Metallic glass has no grain boundaries making it three times stronger than steel and 100 times more elastic so that it retains its form after impact. They melt at low temperatures so may be easily moulded similar to plastic. The crystallisation process must be eliminated which may occur if the molten state is cooled very rapidly. This is enabled by adding large metal atoms such as lanthanum to the alloy which disrupts crystal formation. Vitreloy uses large atoms of Zr, Ti, Cu and Ni with small atoms of Be to generate a strong metal with high eleasticity which is malleable at low temps ~400^{o}C. However, to reduce their brittleness at high enough impact forces (due to shear bands at stress points which are not reduced by disruption at grain boundaries), crystal particles may be embedded. The most promising candidate for a metallic glass is a mixture of Pt, Cu, Ni and P of which 60% is Pt. Other possibilities include steel glass containing Fe, C and small amount of Mn creating a non-magnetic steel.

Optical neural networks of simple nonlinear processing elements capable of adaptive learning offer great promise for direct integration into composite materials [Coghlan 1992]. This effectively offers the integration of avionics into the structures of aerospace systems. Adaptive materials are likely to contribute substantially to these approaches to reliability specifically with regard to structure for in-situ self-diagnosis and repair. Failures may be prevented by the ability to monitor strain, fatigue, damage and delaminations. Optical fibres can continuously monitor composite structures at all stages of their life from manufacture, testing and operational lifetime (health monitoring and biometrics). Sensors must be able to withstand the manufacturing environment without degradation. Self healing fibres have been developed for composites consisting of hollow porous glass fibres filled with adhesive. Shearing of such fibres by crack propagation releases the resin to fill the cracks. Corrosion may be offset by wrapping plastic based fibres around metal reinforcement fibres. Changes in acidity dissolve the fibre coatings releasing chemicals to halt the decay.

10.3. BIOMIMETIC STRUCTURES

Optical technology is a technology that may be adopted in place of or in conjunction with electronics, particularly fibre-optic systems. Light transmission can be controlled in one, two or three dimensions by the periodicity of the material (with periodicity close to the wavelength of light). One and two-dimensional periodicity on a surface defines a diffraction grating. If there exists two or three dimensional periodicity within the material bulk, this defines a photonic crystal in which there are allowed bands of energies separated by bandgaps. Photonic bandgap fibres outperform conventional optical fibres. The same principles of surface periodicity underlie reflective and coloured surfaces in nature [Vukusic 2004]. Insects, butterflies, birds and fish reflecting surfaces are characterised by one dimensional multiplayer periodicity. Surface diffraction gratings appeared in 500 million year old Burgess Shale fossils as near-periodic parallel corrugations on their exoskeletons. Similar diffraction grating surfaces exist today in wasps, flies and moths. The purpose of these surfaces are usually as antireflection surfaces to reduce the reflection of light, eg. insect eyes. The hairs of the shallow water worm Aphrodite are bundles of hollow two dimensional photonic crystal fibres, each of diameter 230 nm. The brittle starfish surface comprises a two dimensional array of microlenses, each a photonic crystal of calcite to collect and focus light while minimising spherical aberration.

The archetypal animal is the worm which comprises a tube with a crossed helical array of fibres around it and have their maximum volume at fibres arranged 54^o from the longitudinal axis [Vincent 2004]. Tubes can be short and fat or long and thin and worms exploit this variability for lcomotion through actuation pressure. Sea anemones, corals and jellyfish exploit the same mechanism to shoot out thin hollow thread at 40,000g using 150 atmosphere nemacyst pressure. The thread has barbs and can deliver poison to the wound. The abdomen of the locust extebds from 2.5 cm to 8 cm in digging a hole in the sand to lay its eggs. The chitin fibres are arranged to resist compressive hoop strains so the longitudinal Poisson's ratio is low ~0.03. The digging organ at the tip acts independently to drill the hole and pulls the abdomen down with it. Wings of insects when transforming into the adult stage expands its wings from short and stubby to long thin stiff membranes by expanding and flattening. Wings can be folded based on the simplest four-fold system of 3 valley and 2 crest fold controlled from the base of the wing with three contact points with the body. They are usually bistable. A fold can be neutralised by running another fold across it. Leaves also expand by control of the orientation of cellulose fibres. Hornbeam and beech leaves are plane surfaces with straight parallel corrugated folds. Almost all biological kinematic articulation mechanisms are based on the planar four-bar linkage with variations in one, two or three bar lengths, eg. jaw of snakes and the angler fish. The proboscis of Lepidoptera is coiled beneath the head and deployed in trough form by pressure applied at the base of the proboscis similar to a steel measuring tape. The spasmonin in the stalk of some single celled animals is not a sliding filament like muscle but relies on the addition of Ca to give an instantaneous power of 2.7 kW/kg compared with muscle which offers 0.05-0.2 kW/kg.

Some spiders spin webs to catch prey passively while others hunt prey, but all spin silk. Spider silk is a composite material constructed from the amino acid alanine polymers embedded in a matrix of the amino acid glycine. Almost half the alanine crystals are aligned parallel to the fibres while other are cross-linked with the matrix molecules. Spider silk is around 10 times tougher than Kevlar.

Gecko's feet are characterised by their highly adhesive pads to enable them to hold onto rough and smooth surfaces [Zhang et al 2004]. The key lies in the microstructure which has the form of hairy brushes with hair diameters of 100-300μm and lengths of 100-200μm. Mechanical inter-locking, van der Waal forces and chemical bonding forces determine adhesion. Chemical bonding enhances adhesive forces by an order of magnitude greater than van der Waal forces. The contact area is given by:

$A = 2\pi\left(\frac{3}{4}\frac{1-v^2}{E}RF_n\right)^{2/3}$ where R=equivalent radius of surface (roughness) (μm)
v=Poisson's ratio
E=Young's modulus
F=mechanical load

Hence ground contact area is enhanced by reduced elastic modulus of the hair. Surface roughness decreases contact area as roughness is quantified as a decrease in equivalent radius. Indeed, maximum surface roughness that can be adhered to is 0.3 μm.

Medusae are predators and hunt and kill their prey using harpoon-like nemacyst cells, primarily in their tentacles. The barbed threads are fired by physical contact and inject venom into the prey. The harpoon is stored coiled within the cell with a small trigger (cnidocil) projecting from it – when tripped, water floods into the cell that makes the thread and its harpoon instantly swell and so discharge. Actuation in spacecraft is generally performed by electric motors and gearing systems. However, they require lubrication which is generally of the dry form. It is well known that reciprocating mechanisms are a source of single point failure modes and as such are regarded as one of the least reliable components on a spacecraft.

The structure of an organism can serve an important function beyond that of mechanical integrity. The cricket has four auditory apertures – the tympani hearing organs are located on each upper foreleg and two spiracles are located on each side of the front part of the body. The four apertures are connected by tracheal tubes. Each tympani receives different signals which are to be discriminated. A delayed version of the same signals is received through the tracheal tubes. The stimuli reinforce or cancel each other according to the relative phase. The length of the tracheal tube is tuned to the wavelength of the desired calling song so all other sounds are filtered out. Furthermore, the amplitude of sound is determined by the travelled distance, giving an indication of the direction of the source. This process has been replicated in a Khepera mobile robot with four microphones to detect a signal and its delayed copy. Thus, structure, sensors, actuators and control system all interact.

Tensegrity (tensional integrity) refers to mechanical stabilisation through the distribution and balance of tensional and compressive forces and stresses within a structure. Tensional stresses are distributed continuously through all parts of the structure. Tensegrity underlies the protein cytoskeleton of the eukaryotic cell which are anchored to integrins embedded in the cell membrane. Contractile microfilaments provide most of the tension inwards while microtubules act as compression struts and keep the nucleus inside the cell. One example is the Buckminster Fuller geodesic dome in which rigid struts connected into triangles, pentagons or hexagons constrain and fix each joint. The buckyball construction of C-60 is formed by 20 hexagons interspersed with 12 pentagons resulting in 90 C-C bonds for a tensegrity structure.

These types of structures hold considerable promise for large scale structures and deployable structures. Although such structures are generally associated with large scale on-orbit applications such as space stations, they may be of relevance to solar sail structures (for instance, for in-space passive propulsion for planetary missions) for high rigidity or planetary habitats. Their application to robotic explorer spacecraft is limited beyond solar sails and deployable structures.

For large deployable structures, gossamer ultra-thin film materials would drastically reduce the weight and volume of antennae and solar panels. Composite materials incorporating carbon nanotubes offer extremely high strength with low weight – such nanotubes can be manufactured in the laboratory up to ~mm in length but represent a long-term technology for large structures. Carbon nanotube is a tubular form of carbon with a diameter ~1 nm with a length of up to ~μm configirationally equivalent to a 2 D graphene sheet rolled into a tube. It is grown by laser ablation, carbon arc and chemical vapour deposition processes. Heat shock proteins (HSP 60) in thernophiles can be purified from cells as double ring structures of 16-18 subunits which can be induced to self-aasemble into nanotubes. Carbon nanmotube has a Young's modulus of ~1 TPa and tensile strength of ~200 GPa. Depending on its chirality, it may be metallic or semiconducting. The C-C covalent bonding into a seamless hexagonal network affords a strong yet flexible structure. Its strength to weight ratio is 500 times that of Al. It has a longitudinal thermal conductivity of ~3000 W/mK and an electrical conductivity a million times that of Cu. Carbon nanotubes offer high durability tips for atomic force microscopy. Zeolite strips or carbon nanotubes may be used to store lightweight radiation-shielding hydrogen without cryogenic cooling. Boron and aluminium could also serve a similar role for other types of radiation. The chief problem for these materials is the lack of understanding on their performance and survivability for long-term space exposure with its variable temperature regimes, vacuum and/or planetary atmosphere flux, and radiation environment. Carbon nanotube material has extreme mechanical properties –

Young's modulus of over 1 Tpa and a tensile strength of 200 GPa. It has a thermal conductivity of ~3000 W/mK. It has tailorable electrical properties, ie. semiconductor or metal. Carbon nanotubes lie outside the scope of this report. Ultra-light structures offer low mass and low stored volume for large area reflectors, solar arrays solar sails, and other deployable structures. Such systems will require membrane tensioning systems, inflation systems and deployment control systems. The family Droseraceae of carnivorous plants such as the Venus Flytrap (Dionaea Muscipula Ellis) is a bio-inspired model of a deployable biomimetic structure with sensors and actuators [Shahinpoor & Thompson 1995]. The Venus Flytrap is capable of trapping and capturing flies by stimulation of trigger hairs which rapidly closes its twin-lobed leaf blades like a spring trap[11]. Such a biomimetic structure may be implemented using ionic polymer membrane composites. Pure passive damping of vibrating structures may be stable but is limited in damping performance – some form of active damping is necessary. Vibration suppression of smart structures in the face of thermal and mechanical vibrations may be achieved through a two neural network controller, one for system identification to model the inverse dynamics and the other for closed loop control [Rao et al 1994]. Such vibration suppression of space truss structures may be achieved through a variable damper based on electrorheological fluid which has variable viscosity according to the applied electric field with a time constant of 10 ms [Onoda et al 1997]. Active control of surface figures for large aperture reflectors is essential to maintain shape to within a fraction of a wavelength determined by diffraction limits, eg. Next Generation (James Webb) Space Telescope which will employ an 8m diameter mirror with shape control to 50 nm [Gorinevsky et al 2001]. A gossamer structure with inbuilt distributed sensors, actuators and computing components may be achieved using local error information. The NGST will require around 100s of such actuators within an areal density of 10 kg/m^2. A rolling contact electrostatic actuator acts as a dielectric capacitor based on polyMEMS technology. The force responsible for movement is produced at the rolling contact. The same principle of rolling contact can be used to produce a pneumatic pump of a chamber and two thin diaphragms for inflatable structures. Control for each cell is computed as the weighted sum of past PI feedback control actions and sensor measurement errors for it and the neighbouring cells. Inflatable structures may also be implemented for flexible robotic manipulators [Rybski et al 1996]. The inflatable shell is composed of composite fabric with perpendicular weaves coated in an elastomer matrix, eg. butyl coated nylon which has a Young's modulus of 100 kg/mm^2, a rupture stress of 11.4 kg/mm^2 and a shear modulus of 4.52 kg/mm^2. Inflation generates a diameter and length change given by:

$\Delta D = \frac{2R^2\Delta P}{Et}$ where R=cylinder radius, t=wall thickness

$\Delta L = \frac{LR\Delta P}{2Et}$

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[11] There are around 600 species of carniviorous plants within 6 angiosperm subclasses generally confined to well-lit moist habitats that are nutrient deprived – indications are that plant carnivory has evolved multiply and independently in different phyla as a form of evolutionary convergence [Ellison & Gotelli 2001]

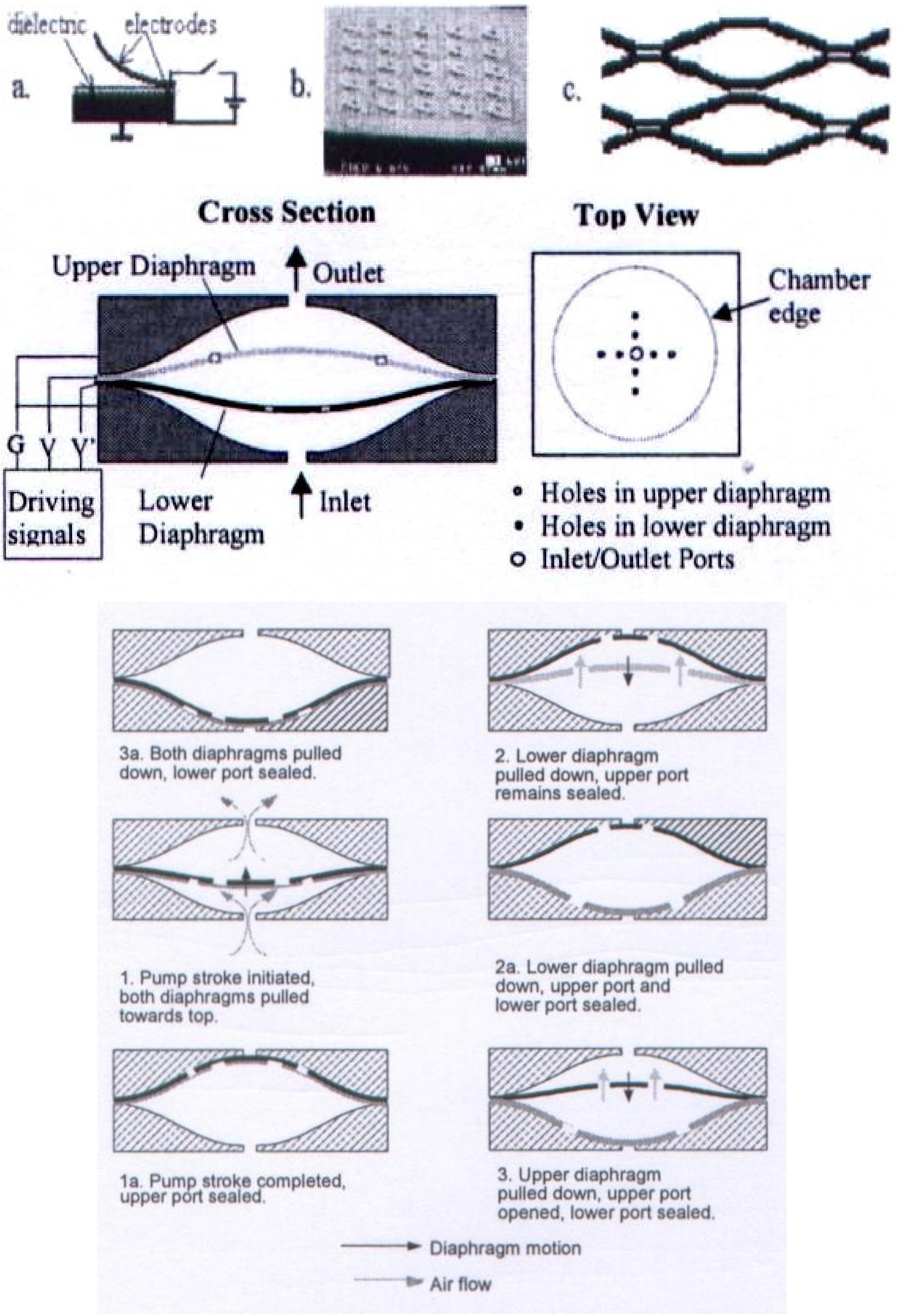


Fig 10-2 (a) Rolling contact electrostatic actuator; (b) Honeywell silicon micromachined actuator array; (c) multilayer polyMEMS electrostatic linear actuator; (d) dual diaphragm pump with through holes and inlet/outlet ports; (e) dual diaphragm pump operation [from Gorinevsky et al 2001]

Ideally, multifunctional materials should synergistically combine a wide variety of functions: sensing, signal transduction, actuation and shape change, as well surface functionalization to selectively respond to various biological and chemical molecules. There are a number of different types of polymer-based actuators based on emulating biological muscles:

(i) McKibben muscle actuators which are air tubes with an angularly braided fibre reinfrcement that contracts when inflated but it suffers from low frequency actuation
(ii) Shape memory alloys which exhibit volume changes under temperature change
(iii) Electrorheological fluids which increase in viscosity under an electric field
(iv) Electroactive polymers, eg. ion exchange membranes, gel polymers, perfluorinated sulphonic polymers, and self-assembled mono-layered polymers

Artificial muscles include a variety of materials and structures. They act as linear motors with damping (braking) and elastic (spring) characteristics, ie. viscoelastic system [Kornbluh et al 2000]. This is the basis of their properties as preflexes with near instantaneous reaction to external perturbations without sensory feedback. Tuning involves efficient interchange between kinetic energy of movement with potential energy stored in elastic elements. Impedance defines the relationship between external applied forces and resulting displacement. Hill's model was a linear impedance model involving only stiffness and damping parameters which allowed separation of static force-length and active force-velocity relations. However, muscles are nonlinear, time-variable systems with complex responses affected by amplitude and frequency with inertial characteristics due to skeletal linkages. Muscles are average power limited to ~100 W/kg but peak powers can be as high as 300 W/kg. Peak contraction velocity of muscle is ~0.3-16 lengths/s. Polymeric dielectric elastomer actuators have high strain, high efficiency, high energy density, fast response, good controllability, good durability and impedance selection but do require high voltages. When a voltage is applied, the polymer shrinks in thickness and area similar to electrostictive polymers. Pressure generated is given by:

$P = \varepsilon_0 \varepsilon_r \left(\frac{V}{t}\right)^2$ where t=film thickness

Maximum power output was 10 W/kg at a frequency of 10 Hz, strain of 2.5% and applied voltage of 5 kV. McKibben actuators are inflatable elastomer tubes surrounded by a braided sheath that is longitudinally stiff. The ends are plugged and the tubes are crimped on the plugs. One plug has a port through which air enters and inflates it causing the tube to expand circumferentially and shorten longitudinally. Their force output decreases with shortening like muscles and have similar strength-to-weight ratios.

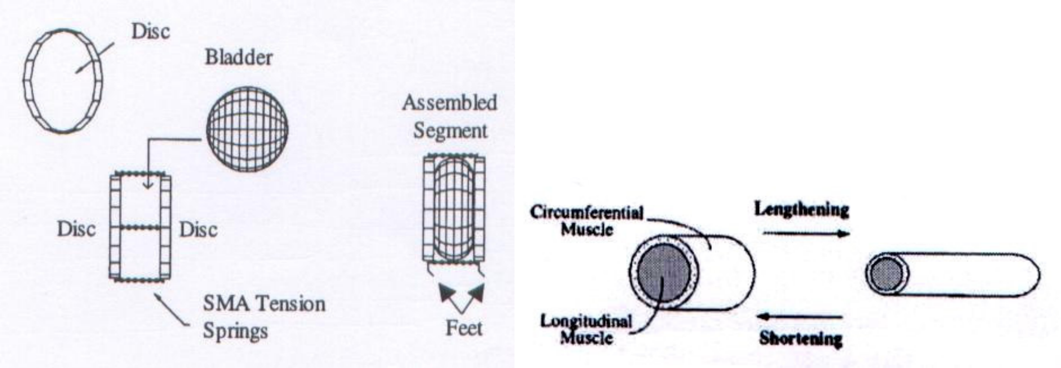


Fig 10-3 Fluid-filled bladders surrounded by SMA wire mesh to act a musculasr hydrostat [from Vaidyanathan et al 2000]

Shape memory alloys such as NiTi in the form of wires may be adopted as artificial muscles [Witting et al 2000]. SMA undergoes a phase transformation from the body-centred cubic austenitic phase to the face centred cubic martensitic phase such that $M_{finish} < M_{start} < A_{start} < A_{finish}$ with increasing temperature. NiTi can recover plastic strains of 8% on deformation due to the martensitic transformation on temperature reduction. If the SMA is cooled to its martensitic phase and subjected to stress, multiple crystal orientations convert into a single orientation determined by the loading axis. On unloading, the plastic strain remains. Heating the material back to its austenitic phase recovers the plastic strain and the material returns to its original shape. The pseudo-elastic effect is based on a critical stress level at $T>M_s$ whereby the ausenitic phase is transformed to the martensitic phase. If the material is unloaded at $T>A_f$ the martensitic phase is transformed back to the austenitic phase with plastic strain recovery. NiTi wire can be heated by passing electric current through it generating the martensitic phase and generating stress in the wire. PolyMEMS actuators (PMA) are comprised of 3D arrays of milliscale cells which are actuated electrostatically which closes each cell (tension only) similar to the combined action of muscle cells and can operate in antagonistic pairs to control joint actuator stiffness like muscles [Horning & Johnson 2000].

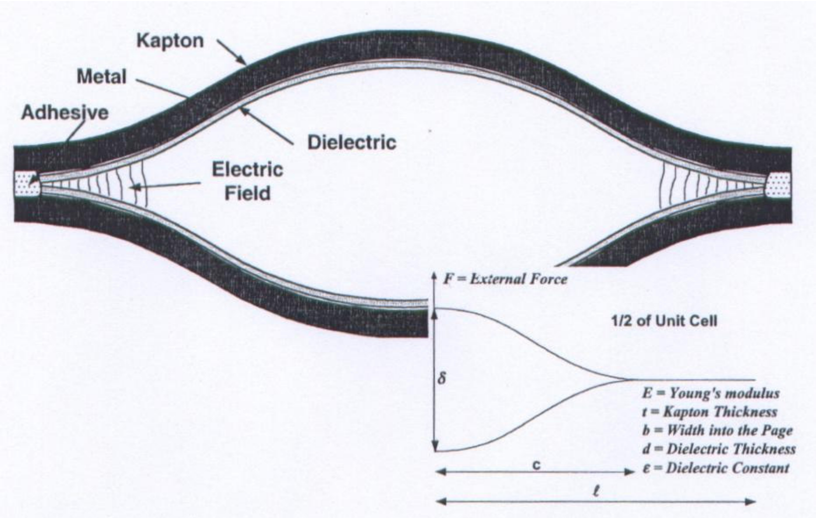


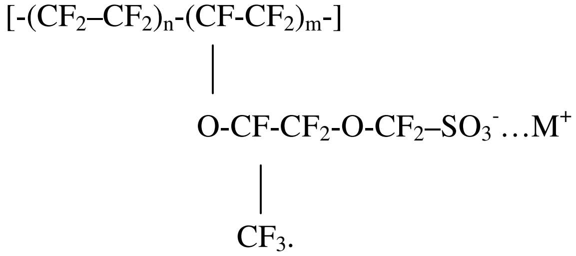
Fig 10-4 Muscle unit cell [from Horning & Johnson 2002]

Pull-in voltage, $V_{pullin} = \sqrt{\left(\frac{6d}{kl\varepsilon_0\varepsilon_r}\right)\frac{F}{b}}$ where d=dielectric thickness ~0.3-1 μm
b=width
k=spring constant
F=external force

Strain, $\frac{\delta}{\delta+2t} = \frac{F}{F+2kbt}$ where t=thickness

With no voltage applied, the unit cell acts as a spring with spring constant kb. An external force F will extend the actuator a distance $\delta = F/kb$. If a small voltage is applied, there is no effect until pull-in voltage is reached when the cell contracts. Polyvinylidene fluoride (PVDF) has ε_r~10 yielding only 150 mW of power at 5 Hz.

The muscle spindle is a group of muscle fibres encapsulated by a collagen sheath with a fusiform shape. The Ia stretch receptor are rapidly adapting and cease firing on cessation of stretch while II stretch receptors is slowly adapting and continues firing after stretching has ceased. Golgi tendon organs monitor muscle tension. Electroactive polymers have many similarities to biological muscles capable of 300% strains and large displacements [Bar-Cohen 2000, 2003a,b, Bar-Cohen & Breazel 2003]. However, EAPs currently lack robustness and reach their stress limits at lower stress levels than shape memory alloys. Ionic polymer-metal composites (IPMC) can undergo large bending displacements if an electric field is applied to act as actuators or conversely, bending can induce a voltage to act as motion sensors [Shahinpoor et al 1998]. They are polyelectrolytes with ionisable groups on their molecular backbone. These ionisable groups dissociate and retain a net charge in a liquid medium. These charge groups are attached to 3D networks of macromolecules – polyions – which generate intense electric fields ~10^{10} V/m. If the interstitial space of a polyelectrolyte network is filled with polar liquid containing ions, then electrophoretic migration of ions inside the structure due to an imposed electric field causes the network to deform. They require a humid environment but encapsulation allows their use in dry environments. The relationship is linear and maximum displacement occurs at its resonant frequency (20 Hz). The most promising EAP material is ion exchange membrane metallic composites of perfluorocarboxylate-gold with two types of cations, tetra-n-butylammonium and lithium which requires only 3V square wave potential difference to actuate:



$$\begin{array}{l}[-(CF_2{-}CF_2)_n\text{-}(CF\text{-}CF_2)_m\text{-}]\\ \qquad\qquad\qquad |\\ \qquad\qquad\qquad O\text{-}CF\text{-}CF_2\text{-}O\text{-}CF_2{-}SO_3^{-}\ldots M^{+}\\ \qquad\qquad\qquad\quad |\\ \qquad\qquad\qquad\quad CF_3.\end{array}$$

where $5<n<11$ and $m\sim1$ and M^+=counter-ion such as H^+, Li^+ or Na^+. The overall reaction is given by:

$LiBH_4 + 4[Pt(NH_3)_4]^{2+} + 8OH^- \rightarrow 4Pt^0(s) + 16NH_3(g) + LiBO_2(s) + 6H_2O(l)$

$LiBH_4 + 4H_2O \rightarrow 4H_2 + LiOH\ (Li^+ + OH^-) + B(OH)_3(s)$

Strain is defined as: $e = e_c \pm K\eta = \lambda - 1$ where e_c=neutral centreline strain, K=curvature, η=cross-section, λ=stretch

A simple model of electrically induced deformation of ionic polymeric gels is given by axial stress [Shahinpoor 1994]:

$$\sigma = \tfrac{1}{3}E(C_0, C_i)(\lambda - \lambda^{-2})$$

$$\sigma = k(C_0, C_i)E_f^{\ 2}$$

where σ=stress, E=Young's modulus, C=polymer/ion concentration, k=electromechanical coefficient, E_f=local electric field

IPMCs can operate at temperatures of –140°C and very low pressures. Biological muscles have peak stress levels of 150-300 kPa at a strain of 25%, maximum power output of 150-225 W/kg, average power output of 50 W/kg, energy density of 20-70 J/kg and a contraction speed of 0.1-1s. Intrinsically conducting polymers (ICPs) and polyelectrolyte networks (PN) both possess sensing and actuation properties that have been demonstrated individually. Furthermore, their charged nature allows for facile combination with each other as well as surface modification and functionalization to incorporate various sensing and/or gating molecules. They can also be processed into a range of forms including films, filaments and micro and nano-particles, depending on the targeted application. The challenge would now be to effectively couple these various properties and functionalities synergistically into a single working unit. There is the potential to exploit and integrate the various features of ICP and PNs by using novel chemical and electrochemical design techniques and mimicking select sensing and actuation mechanisms found in nature. In oxidized form, conducting polymers carry positive charges along their highly conjugated backbone[1]. In its oxidized form, polypyrrole is a polycation with delocalized positive charges along the backbone. This allows for electron transfer between different chains, thus giving rise to electronic conduction. This backbone permits electron transfer between different chains, giving rise to electronic conduction. Conducting polymers undergo redox changes in response to oppositely-charged counterions. The intercalation of oppositely-charged ions leads to small volume changes.

To date conducting polymers, especially polypyrrole (shown above) have been considered for a variety of applications including biosensors, sensing volatile chemicals, tranducers in implantable medical devices and as micro-actuators. Hydrogels are three-dimensional polymer networks swollen in water. Their ability to reversibly collapse in response to an environmental stimulus have earned them the moniker "smart gels". Polyelectrolye hydrogels-swollen polymer networks bearing charged groups may be used for actruation. Their remarkable ability to reversibly shrink or swell in the presence of oppositely-charged counter-ions via **ion-exchange** bears a remarkable resemblance to some of the mechanisms found in living tissue, such as nerve excitation[3], swelling of the cornea[4] and cartilage[5], and muscle contraction[6]. In addition, the locomotive mechanisms in so-called "hydrostatic animals" like eels and squids, can also be attributed to a hydrogel-like swollen/collapsed phase transition[7]. This phase transition property, coupled with their soft, hydrated, tissue-like texture, make polyelectrolyte hydrogels promising candidates for replacing soft living tissues. Preliminary work by Rajagopalan et al.[6] on implantable artificial muscles is striking parallels between muscle contraction and ion exchange in polyelectrolyte gels. With two established theories in muscle physiology, namely (a) Hill's model and (b) Huxley's sliding filament theory as paradigms, a composite interpenetrating polymer network with contractile and elastic components was developed. The composite network contracts in an "all-or-nothing" manner with a critical concentration of Ca^{2+}, while relaxation is brought about via Na^+/Ca^{2+} ion exchange, both defining properties of biological muscles. The basic biomechanical profile of the artificial muscle bears striking resemblance to that of biological muscles – namely a non-linear force-displacement profile and an abrupt increase in stiffness on contraction.

While the active properties of both these classes of materials have been demonstrated individually, their multifunctionality as a combined unit has yet to be explored. Since ICP and PNs can be easily combined through electrostatic interaction and covalent bonding, their respective active properties are complementary and can be effectively coupled into a single multifunctional unit. For instance a conducting polymer such a polypyrrole, electrochemically doped with counterions, could serve as a flexible electrode and ion reservoir to trigger volume and changes in the polyelectrolyte network. Alternatively, the abrupt volume change in the PN due to the presence of ions or biomolecules, could change the redox state of the adhering conducting polymer, which could be detected electrically.

10.4. MECHANICAL COMPLIANCE

Interaction with the real world environment imposes the need for force control – traditionally, spacecraft have been sensor platforms, but the introduction of robotic systems which interact with their environments implies the need to control that interaction. Environment stiffness K_e is often high ~10^6N/m which produces little damping but give high natural frequency responses generating poor stability. Low stiffness environments still give K_e~10^5N/m and such enivironments are often determined by both the object stiffness K_0 and the manipulator compliance K_m: $\frac{1}{K_e} = \frac{1}{K_o} + \frac{1}{K_m} \to K_e = \frac{K_m K_o}{K_m + K_o}$. To deal with stiff environments with high K_e, force gain K_F must be small. Generally, a fixed force gain is not ideal: the value of K_F will differ depending on the contact dynamics between the manipulator and the environment. As stiffness of contact increases, so K_F should be reduced. Without a priori knowledge of the environmental stiffness, K_F should be set as low as possible, but in softer environments this will result in slower response times.

All force feedback schemes introduce time delays which in human muscular control amounts to 50-100 ms. High gains together with such time delays can introduce instabilities due to oscillation. Typically, the best force control scheme includes an integral gain component to act as a low pass filter, which is effective in filtering out high frequency components of noise-prone force sensors for low energy force changes. The proportional component reduces the lag of the integral controller, though the integral only controller performs well. Damping is incorporated through the position control system and, indeed, it has been proposed that the stretch reflex requires such direct velocity feedback to provide such damping [Clark 1994]. There are two types of unified force control approaches– impedance control and hybrid position force control. In animal muscle, force and length are the two main motion control variables and these two variables are related as force varies with muscle length according to the overlap of thin and thick muscle filaments [Stein 1982]. This implies stiffness control in muscles. However, force also varies with the velocity of motion according to Hill's force-velocity curve and velocity feedback prevents the instabilities that occur due to phase lags and to rapidly variable loadings on the muscle [Hill 1938, 1953]. This implies viscosity control of force-to-velocity. The force-velocity relationship gives rapid drop in force with increasing shortening velocity and rapid rise in force when muscles lengthen which acts as a "brake" to decelerate movement. Central pattern generators control mechanical impedance (stiffness and viscosity) by determining the muscular state of activation over time. Mechanical impedance control is equivalent to the simultaneous control of position, force and velocity and provides a simultaneous position servo for high stiffness and force servo for high compliance. Impedance control provides a simplified Hill type model in which muscular contractile fibres exert force depending on the length of the fibre modelled as a stiff spring, the speed of contraction and muscle activation level. Muscle tension through agonist/antagonist muscle pairings applied to the momentum arm of the limb produces the joint torque. The muscle model must encapsulate force-velocity, series visco-elasticity, torque-angle and neural activity properties [Winters & Stark 1985]. The force exerted by the muscle is given by:

$F = F_{\max}\alpha(l_m - t^s)\beta(\dot{l}_m)a(t)$ where F_{max} = peak isometric force
t_s = tendon spring length
l_m = total muscle fibre length
a(t) = muscle activation level such that $0 \le a(t) \le 1$
$\alpha = 1 - \left(\frac{x - l_0}{w l_0}\right)^2$ = force-length relation
l_0 = optimal muscle fibre length
w = operation range parameter, typically 0.65
β = rectangular hyperbola force-velocity relation such
that: $(a_f + \beta)\left(\frac{v}{v_m} + a_f\right) = (a_f + 1)a_f$

v = shortening velocity
v_m = 2l_o to 8l_o depending on fibre type contractile speed
a_f = 0.25

For arrays of muscle fibres, physiological cross sectional area (PCSA) gives a measure of isometric muscle force output:

$$PCSA(mm^2) = \frac{M(g).\cos\theta}{\rho(g/mm^3).L_f(mm)}$$ where M = muscle mass

ρ = muscle density = 1.056 g/cm^3
θ = surface pennation angle (angle between line of action and myofibre long axis) = 0 to 30^o
L_f = myofibre length

Skeletal muscle comprises fibres ~1-50 mm in length and 10-100 μm in diameter. Each muscle fibre is constructed from a large number of myofibrils of 1-2 μm in diameter. Muscle is contractile only and is composed of two overlapping protein filaments— actin thin filaments of molecular weight 70,000 and length 1.9 μm and myosin thick filaments of molecular weight of 450,000 and length 1.65 μm. Cross-bridges from the myosin filaments into the actin filaments provides the basis for force generation through relative movement of the two filaments so overlap is necessary, ie. maximum length of muscle fibre is 3.65 μm while maximum force generation of around 250 kPa (5 pN across 0.5 μm cross section) occurs at a muscle fibre length of 2.0 μm generating a relative displacement of 0.5-1.0 μm [Lieber 1999]. On contraction, actomyosin is formed which shortens by 20-40% on the addition of ATP within 50 ms, though higher rates of 1 ms are achievable for insect muscles. The mechanical efficiency of muscular contraction is around 45-75% and offers 40-100 W/kg specific power performance. Once again, insect flight muscles offer higher power densities of 60-200 W/kg with a cycle frequency of 30-40 Hz. The mechanical dynamics of muscle are determined by the ratio of the maximum shortening velocity and elastic stretch, both being proportional to the muscle fibre length. The maximum isometric stress within a human muscle is ~40-100 N/cm^2. Often muscles act over two joints, eg. the bicep and tricep cross the shoulder joint – the muscle on the proximal joint steadies this joint (eg. shoulder) while acting as prime mover on the more distal joint (eg. elbow). All animal muscle comprises three types – smooth (visceral) muscle is supplied by autonomic nerves which are present as a nerve plexus which innervates a sheet of smooth muscle, striated (skeletal) muscle is supplied by voluntary nerves which end in a neuromuscular plate through which motor nerve potential exceeding a threshold are passed to generate a muscle action potential through the muscle fibre, while cardiac muscle (which is striated) is supplied by autonomic nerves which pace the natural rhythm of contraction. Skeletal muscle operates in an "all or nothing" fashion such that the degree of contraction of the muscle is dependent on the number of muscle fibres. Furthermore, Hilton's law suggests that motor nerves which supply innervation to muscle also supply signals to the joint over which the muscle passes and to the skin over the joint to aid movement. Montemagno (2002) has proposed the use of engineered muscle fibres for actuation, manufactured by the MEMS technology, SCREAM (single crystal reactive etching and metallisation) process but has had limited success.

Impedance control is a methodology for robotic control based on a biological paradigm [Hogan et al 1985]. The cerebellum stores muscle activation patterns learned from the association of proprioceptive stimuli indicating co-contraction of agonist-antagonist muscle lengths. Modulation of contraction in the timing and amplitude of muscle activity regulates the visco-elastic properties of the joints to move between postures. Muscles behave as tunable springs by virtue of their arrangement around joints in agonistic/antagonistic pairs. The elasticity of the muscle is determined by its activation level which determines their length-extension α which in turn defines the equilibrium position and stiffness of the joint. This may be modelled as a potential function of the joint angle, the negative derivative of which is the generalised force. The postural force field is characterised by the product of a displacement vector and a stiffness matrix. Activation of agonistic/antagonistic muscles determines the potential minimum (determined by the α ratio) and the potential minimum curvature (determined by the α sum). Displacement from the potential minimum results in a restoring torque independent of feedback. Thus all control acts through a single time-dependent potential function with the muscles themselves computing the joint torques. The function of the nervous system is to transform the desired trajectory into a sequence of joint equilibrium positions and stiffnesses determined by a global time-dependent potential function. This method of hybrid position/force (impedance) control is still under development though offers great promise. It provides a unified framework for all kinds of manipulator motion involving dynamic interactions while preserving stability during interactions with the dynamic environment. However, it is important to note that biologically, such control of joint viscoelastic properties is achieved by feedforward open loop mechanisms from learned cerebellar inverse dynamics models due to delays and instabilities in online feedback mechanisms.

One way to reduce $K_F K_e$ is to introduce passive compliance at the wrist to reduce the effective environmental stiffness, ie. a remote centre compliance (RCC). The compliance aspect offers an additional passive component to active control that is generally absent in artificially engineered machines. This approach to compliant structures offers greater freedom in the selection of control parameters and the distributed sensor approach offers the controller greater prospects for closed loop controllability. Animal limb movements are often modelled through impedance (or equivalently force) control.

11. Spacecraft Payloads (Sensors)

11.1. INTRODUCTION

On the basis that most space payloads are sensors – for Earth observation and solar system exploration missions - we provide a brief assessment of biological issues for sensor payloads. The sensors provide information from the physical environment to ensure appropriate actions are taken to ensure both survival and the performance of the required tasks. This physical world is only partially observable – the component of observability is determined by the sensor suite adopted. This is the reason we have chosen to ignore Artificial Life research in this document as it is restricted to simulations in highly simplified environments which do not capture the complexities of the real world. In classifying spacecraft payload sensors, we note that most are remote sensing devices which detect electromagnetic emissions from sources. Communication satellites use radiofrequency transmitter/receiver devices (as do navigation satellites). Earth observation (including meteorological) spacecraft generally adopt optical and microwave detection methods as these are the only regions of the electromagnetic spectrum to which the Earth's atmosphere are transparent. Astronomy missions use detectors from across the electromagnetic spectrum – radiofrequency, submillimetre, far infared, infrared, optical, ultraviolet, X-rays and gamma rays. The dominant sensor modes are thus radiofrequency and optical wavebands. Radiofrequency is not utilised in biology as it requires large area for generation of such long wavelengths. Optical wavebands have the obvious biomimetic version in biological vision (and near infrared and near ultraviolet). Only planetary science spacecraft and landers utilise more sophisticated in-situ type detectors which are not associated with the electromagnetic spectrum. Remote sensing data is highly suited to rule-based expert system implementation where knowledge is represented as production rules and frames in a database [Goodenough et al 1987]. Production rules have the form (condition then conclusion) with an inferencing engine. A blackboard stores goals from high-level experts and a meta-rule interpreter which determines applicable strategies. A unified representation scheme is generated through pre-processing the image map and segment it into similar regions. The symbolic segments – including attributes such as location, size, shape, boundary - may be used by the rule-base for interpretation.

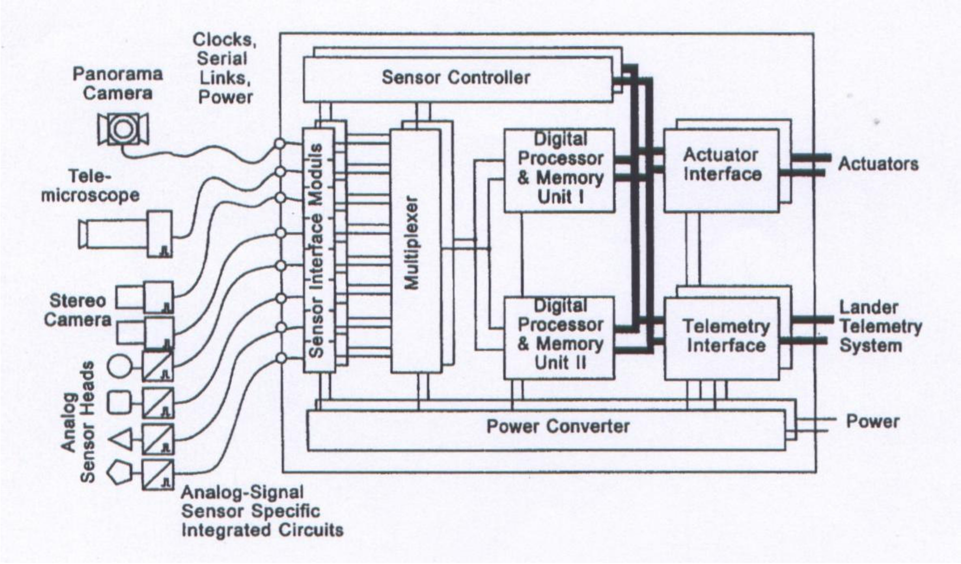
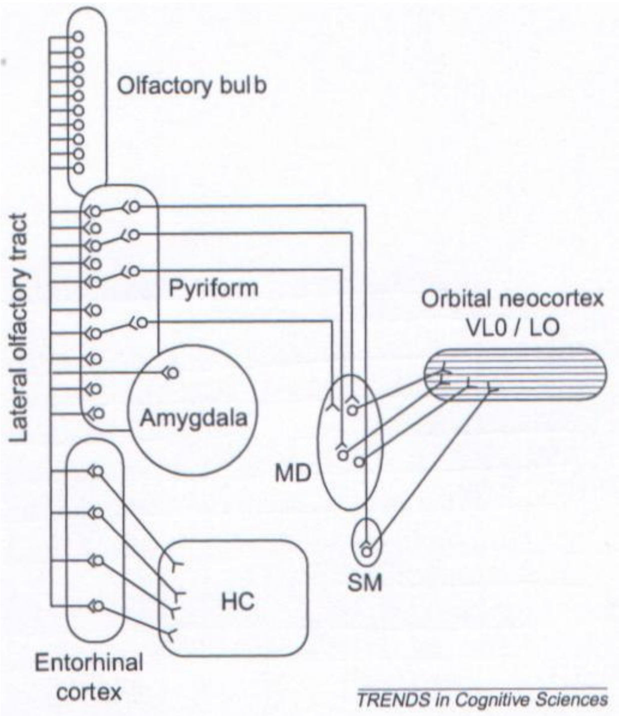


Fig 11-1 Integrated sensor control system architecture

The human visual system is able to group stimuli by similarity, ie. categorise, without external supervision. Indeed, it is clear that categories are not fixed but are fuzzy – the transition between clusters is sigmoidal. Clustering algorithms determine classification on the basis of feature similarity according to distance metrics defining within-cluster variance to between-cluster variance ratio. Categorisation is one of the most fundamental perceptual skills by which organisms assign objects and events to different classes [Ashby & Ell 2001].



TRENDS in Cognitive Sciences

Fig 11-2 Schematic of projections frommain olfactory bulb to olfactory cortex and to thalamic mediodorsal and submedius nuclei and limbic system [from Asby & Ell 2001]

The formation of categories from sensory stimuli is based on the logarithm likelihood ratio [Gold & Shadlen 2001]. Deciding whether a sensory stimulus exists h_1 or not h_2 requires assessment of the evidence e at the detector which determines the likelihood of each hypothesis. Likelihood is the conditional probability of obtaining e given an hypothesis:

$LR_{1,2|e} = \frac{P(e|h_1)}{P(e|h_2)}$ describes the likehood that e is obtained if h_1 were true relative to that if h_2 were true. If LR>1, then h_1 is more likely than h_2, otherwise h_2 is more likely. If prior probability of h_1, independent of e, is known, this relation must be skewed such that:

$$LR_{1,2|e_1} > \frac{P(h_1)}{P(h_2)} = \frac{\exp\left(-\frac{1}{2\sigma^2}(e_1-\mu_1)^2\right)}{\exp\left(-\frac{1}{2\sigma^2}(e_1-\mu_2)^2\right)}$$

The brain can readily compute log(LR):

$\log(LR)_{1,2|e_1} = -\frac{1}{2\sigma^2}\left(2e_1(\mu_2-\mu_1)+\mu_1^2-\mu_2^2\right)$ where e_1 = sensory neuron spike response

When $e_1 > \frac{\mu_1+\mu_2}{2}$ or log(LR) > 0, h_1 is favoured, otherwise h_2 is favoured. This may be extended to incorporate information from multiple sources through the additive principle of logarithms. The most likely location for these types of computation reside in the parietal and frontal association cortex.

The sensing sequence comprises two stages: transduction where the environment properties' effect on the sensor (its state parameter) is converted to an electrical signal (measurement), and signal processing. The three most important measurements are displacement, temperature, and radiation. Displacement measurement is of fundamental importance as it provides the basis for velocity, acceleration, strain, force and pressure measurements sometimes in conjunction with time measurements by piezoelectric quartz oscillators and/or Schmidt trigger. Artificial neural networks have been used for space instrumentation – a software implementation to perform rapid autocorrelation function computations was flown on the Space Shuttle in 1992 [Gough 1993]. A 32-bit neuron input network was implemented on RAM memory units acting as neurons for pattern recognition. The sparsely connected network implemented with N bit addresses for each RAM unit. The 32 point input layer was randomly connected to 16 associative memory units which provided 8-bit outputs. Ninety-six training patterns were used to train the network. The ANN took up 4 kbytes of PROM and used an 8 MHz 80C86 processor to provide rapid computations in 4 ms.

11.2. MICRO-ELECTROMECHANICAL SENSOR/ACTUATOR SYSTEMS

MEMS (Micro-ElectroMechanical Systems) technology offers a promising technology for scientific instrumentation – miniature mechatronic systems which incorporate sensors and/or actuators with signal conditioning and processing electronics. Micro-machining allows the creation of intricate structures in a silicon chip. Multi-chip modules may be constructed using thin-film/thick-film hybrid techniques to make 3D chip structures. MEMS are often used in safety critical applications so usually employ built-in self-test (BIST) functions. A typical MEMS device is the micro-accelerometer.

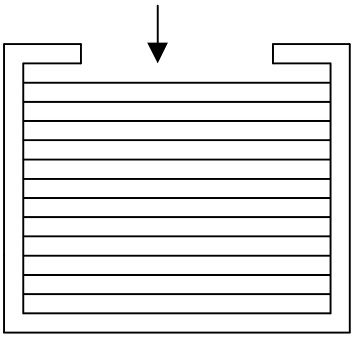


Fig 11-3 Multi-chip architectures – (each layer performs a particular function such as transduction, ASIC, micro-controller, i/o, etc)

Micro-electromechanical systems (MEMS) offer a dramatic development in space robotics as an enabling technology. Space exploration has traditionally provided a driver towards the miniaturisation of technology to reduce the mass of launching payloads into space (and so cost) and such techniques have extensive applications in the medical, environmental and automotive industries. Miniaturisation of sensors, actuators and microelectronics to micron-size offer reduced mass, volume (and so launch costs) and power requirements, and the potential for batch processing and mass production of common off-the-shelf integrated microsystems with increased reliability [de Aragon 1994]. There has been a tendency to employ dedicated electronics integrated with the sensor to make them "smart", eg. in the internal combustion engine [Wolbar & Wise 1979]. Such dedicated processors may be integrated by common interfaces to ensure the millisecond processing time required for real time performance within a dynamic environment.

MEMS are devices with physical dimensions of less than 1 mm which operate on mechanical principles [Angell et 1983]. Microsensing is a new advanced sensor technology that is rapidly becoming available based on electronic integrated circuit batch-fabrication technology. The next generation of sensors will be based on silicon which is abundant and cheap. Silicon is an effective material for transducing many physical phenomena such as light intensity, pressure, force and temperature. Furthermore, pure silicon has the hardness, Young's modulus of elasticity of 1.9 x 10^{12} dyne/cm^2 and tensile strength of 6.9 x 10^{10} dyne/cm^2 similar to stainless steel, ie. several times that of iron or glass. Corrosion-resistant, tough, wear-resistant thin films like SiC or Si_3N_4 can be used to provide a casing for such silicon devices [Petersen 1982]. Si_3N_4 has a hardness second only to diamond.

Pressure sensing is the best developed of such sensors, most of which are based on the piezoelectric effect. They provide 60 times the sensitivity of geometrical deformation sensors. A thin piezoresistive membrane ~10-50μ is etched on a silicon wafer with four silicon strain guage resistors ion implanted in a wheatstone bridge configuration with aluminium interconnects. The electrical resistance of the diaphragm changes when the diaphragm flexes. MOS-based amplifying electronics can be implemented on chip in a similar manner. Accelerometers may also be constructed with piezoresistive materials by replacing the membrane with a silicon oxide cantilever attached to a gold layer proof mass at the end of the cantilever sealed in a cavity. Vibration in the direction of the accelerometer's axis of symmetry generating a shear stress in the piezoelectric crystal. This deforms the crystal, altering its electric polarizability and generating an electric current due to the crystal's assymetric strain tensor. Alternatively, a metal layer may be deposited on top of the oxide cantilever so that the metal layer and the Si layer at the bottom of the well act as two plates of a capacitor. The voltage output is proportional to its acceleration. Such capacitative pressure sensors are more sensitive than piezoresistive sensors. The resonant frequency of the cantilever beam is given by: $f_R = 0.162 \frac{t}{l^2}\sqrt{\frac{E}{\rho}}$. Once the resonant frequency is measured, and the dimensions of the beam known, Young's modulus of the beam material can be computed. A MEMS based pressure sensor based on a Si capacitative transducer has been included in the Deep Space 2 mission with a pressure range of 0-12 mbar as a meteorological pressure sensor. It draws a power of only 20 mW and has an operational temperature range of –80-50^{o}C. New manufacturing techniques allow the construction of suspended or moveable 3D structures. Thin diaphragms, cantilever beams and other 3D mechanical microstructures can thus be etched in silicon or other materials. Mechanical sensors with cantilevers and diaphragms form the largest type of microsensor for displacement and pressure measurements.

Such silicon-based microsensors are able to utilise piezoresistive and piezoelectric effects in relation to applied stress, capacitance changes from pressure and thermal resistance which varies as a function of temperature, all of which may be used to measure pressure and pressure-derived parameters such as force, acceleration and fluid flow. Other capabilities include magnetoresistance and Hall effect voltage generation by applied magnetic fields. Ion-selective FET Si chemical/biological sensors offer the capability of measuring the concentration of ionic and gaseous species though these are less well developed and are presently limited to gas detection, humidity and pH measurements. Thin film processes have been developed to measure thermal, radiation, mechanical, magnetic and chemical signals.

Microsensors are small and of high accuracy with reduced noise and leakage. Such solid state sensors produce low level analogue outputs so signal conditioning electronics such as amplifiers are required. In addition, they offer the capability of secondary parameter (eg. temperature) compensation through the use of standard electronic components such as resistors, diodes and transistors – normally resistive bridge circuits are used to compensate for temperature variations. They are constructed similarly to VLSI microprocessor chips through conventional photolithography and so allow the close integration of electronic and mechanical components. Even complex signal processing functions such as A/D conversion may be achieved through dedicated processors integrated and manufactured with the sensor. This gives them the name "smart" sensors in that the transducer that converts the physical quantity into the electrical voltage signal is integrated onto the same chip and the signal conditioning electronics. MEMS technology exploits the conversion of electrical signals and mechanical forces.

The development of Si microactuators $\sim \mu m^2 - mm^2$ are a logical extension of the more established microsensor technology. Such microactuators are mechanical devices that can allow motion control over very small distances ~0.01-10μ. There are ten actuation methods of transforming energy into motion [Gilbertson & Bisch 1996]. Electromagnetic devices include electric motors, solenoids and relays. They exhibit fast operational speeds with high efficiency but require perpendicularity between a current conductor and the moving element making it difficult to manufacture in planar silicon. An example is the micro-valve which uses a small electromagnetic coil wrapped around a silicon micromechanical valve structure. Electrostatic devices use charge buildup due to free electron flow and include silicon micro-stepper motors with a rotor ~100μ in diameter operating at 25-36 V with speeds of 2500-15000 rpm to generate torques of up to 13 pNm. Electrostatic devices exert great forces over very short distances with low current consumption. These devices offer ~10^3 Hz cycle rates. Thermomechanical devices utilise the expansion/contraction of materials during temperature changes such as bimetallic thermostats. A micro Stirling cycle gas heat engine with high efficiency has been constructed which can act in reverse as cooling systems. Bimetallic cantilever microactuators of gold on silicon with length ~500μ and deflection ~100μ using 200 mW of power. A 200μ long cantilever microactuator of silicon, silicon dioxide and p-doped silicon can produce deflections of 4μ. Temperature changes may be induced by resistive heating, ultrasonic heating or radioactive heating. Examples include paraffin heat pipes. Phase change devices use dimension changes of materials between different states of matter such as a micro-steam engine which has been developed which uses small ~2-60μ resistive heaters to heat a non-conductive F-based cooling fluid to create small gas bubble of ~34-76μ diameter to lift an etched Si plate up by 25μ using only ~20-40 mW of power. It can be fully cycled at 10 Hz. Phase change devices offer very high forces but do require cooling for reverse transformation. A multi-element pin-jointed crank has been constructed with the crank arm being 50μ long with the pin joint being made of a hub around which another element is free to rotate. Such micromechanical devices are based on the construction of micrometer-sized structures including valves, turbopumps, gear-wheels, rotor-based motors and micromanipulators. Integration of microactuators with microsensors offer complete systems and a powerful miniaturisation technology. However, Si requires protection in hostile chemical environments. Gear trains, motors and actuators at the micron scale have been constructed using Ni and Cr metal alloys, ceramics and plastics for different environments. Copper vapour lasers may be used for micromachining of diverse materials. They operate at visible wavelengths (either 578 nm or 510 nm at yellow and green respectively) with high pulse rates ~40 kHz offering ~10μ deep cutting with no heat damage due to glassification to peripheral areas. These lasers have high gain and efficiencies and visible wavelength operation implies that material reflectivity is low at ~50%. A 12:18 electrostatic micromotors of thickness 2.5μ with a rotor ~100μ diameter and a stator-rotor gap of 2μ can provide torques of ~0.25 μN [Lawes 1998]. The IBM inkjet nozzles are also manufactured via MEMS fabrication methods. Superconductor materials exhibit diamagnetism (Meissner effect) – this is the ability to reflect external magnetic fields. In fact, some non-conducting materials such as Bi, Si and graphite possess this ability at very levels at low temperatures. It could be exploited in MEMS devices to levitate magnets against gravity such as frictionless, self-levitating bearings to prevent stiction and friction without lubrication. A microscale high temperature superconducting linear actuator of YBCO has been demonstrated in the form of a 1x1x10mm slider levitating 1mm and being driven horizontally with 30 mg of force. The most developed technologies are electromagnetic, electrostatic and piezoelectric devices typically requiring ~100V to generate proportional forces with rapid actuation and low power consumption.

It is the integration of electronic and mechanical systems including signal processing electronics on a single silicon wafer that gives these devices the name micro-electromechanical systems (MEMS). Function often imposes a limit to physical size reduction, eg. an antenna requires a certain aperture area in order to function effectively. MEMS technologies often involve redesign of macro-system technologies – often rotating masses can be replaced with vibrating combs and tuning forks in microgyroscopes and micro-accelerometers. Friction is the biggest problem for MEMS which can destroy their functioning. Stiction is a similar problem where small electric charges can pull components together and weak chemical bonds can form bewteen them. Small electromagnets must usually be incorporated to levitate objects and components to keep them operational. Another approach is to coat the components with thin films of teflon. Distributed arrays of MEMS offer a integrated systems approach for spacecraft payloads, although they may not offer sufficient forces and torques for some applications.

The chief problem with space-rated MEMS in space is their high susceptibility to radiation. However, the US Air Force has developed a technology demonstration programme Miniature Technology Sensor Integration (TSI) to develop micro-sensor technologies in missile detection and tracking for the BMDO programme. These include visible imaging spectrometers and short and medium infrared imagers, much of the experience coming from the Clementine programme. The Space Bioreactor of dimensions 84x60x60 mm with a 3V electric power requirement is one example of such technologies which includes a micropump for fluid circulation and microsensors to monitor parameter changes in the reactor chamber (STS-65). A MEMS-based capillary gas chromatograph devices have been developed for in-situ chemical analysis of amino acids [Spiering et al 1998, Angell et al 1989, Harrison et al 1993]. Such technologies offer great promise for planetary landers and rovers. The gas chromatograph separate, identifies and measures the quantity of a gas mixture sample. A 5 nl gas sample is injected by an electrokinetic pump from a sample vial through a valve into a long capillary column which is lined with silicone oil in which different gases have different degrees of solubility. The time a gas remains adsorbed depends on its solubility. The gas chromatograph has a long spiral capillary column of 1.5cm length and 10x30μ cross-section formed by adding a groove ~200μ wide and 40μ deep etched in the Si wafer, followed by chemical vapour deposition of silicon nitride onto the wafer. Then the wafer was anodically bonded to the glass capillary. The glass column and Si wafer are heated to 400^{o}C with a negative voltage ~1200 V applied to the glass to anodically bond the two surfaces. The negative charge of the glass fuses the glass and silicon together to form a hermetic seal. The detector is a thin film metal resistor on a thermally isolating membrane of pyrex glass. A constant electric current is passed through the resistor and as the gas sample has a lower thermal conductivity than the He carrier gas, the resistance increases when the sample gas is output through the column, thereby providing a measure of the gas's thermal conductivity. The total integrated chemical laboratory device is fabricated on a 5cm^2 wafer and involves no moving parts.

11.3. VISION SYSTEMS

Vision is the most information-rich form of sensory data. Vision provides the mechanism to obtain distance information to enable strategic rather than tactical behaviour. There are variations in vision systems that do not fit the classification of mammalian vision with direactable eyes or insect vision by optic flow. For instance, owls have cylindrical eyes to give long focal length but have narrower field of view. They cannot swivel their eyes but can swivel their necks through 270^o. Spiders possess 8 eyes in two rows but many spiders including jumping spiders which have two of them as dominant eyes. Humans are primarily visual information processing animals – the ratio of visual to auditory pathway fibres to the brain is ~30:1. The human retina comprises ~10^7 rod cell receptors distributed over the retinal surface for grey level discrimination and ~10^6 cone cell receptors clustered near the fovea for colour discrimination. Indeed, humans have better night vision than most vertebrates. The human eye is capable of receiving and interpreting ~7 x 10^8 bits with a resolution equivalent to 6000 x 6000 pixels with 1 x 10^6 colour levels. The Falconiforme order of birds (raptors) generally have extremely good binocular vision with a visual acuity some two to eight times greater than humans due to the high density of cone cells in their retinas. The standard photovisual filter is usually the UBV filter which ranges across the visible and near uv regimes offering tripeak (red, green and blue) maximum response at 3650, 4400, and 5500 A. One of the most difficult problems in vision systems is determining what features are characteristic of an object which can generate huge variation and ambiguity in sensory patterns. This is the basis of object recognition. The sensorimotor approach asserts that perception and action are tightly coupled so that perception is not passive but motor actions structure perceptions and ground them in the real world. It is this relationship between perception and action that provides invariants.

The mammalian visual system comprises two types of neurons within the retina: horizontal neurons and amacrine neurons which are laterally connected. Stimulation of rods and cones generates receptor potentials which induce signals in both bipolar and horizontal neurons. Bipolar neurons transmit excitatory signals to the ganglion neurons while horizontal neurons transmit excitatory signals to the bipolar neurons. This lateral inhibition enhances contrasts in the visual scene. There are three separate visual pathways – object shape, object colour and object localisation. Similarity between two images is given by:

$$\Delta I(x,y) = | I_1(x,y) - I_2(x,y) |$$

Vision may be defined as the process that produces a representation of the external world from images that is not cluttered with irrelevant information. Colour is often a good approximation to reflectance. The retinex theory of colour vision illustrates the way humans estimate colour under a wide variety of intensities by using surface reflectance at different wavelength distributions. Red, green and blue digital colour images are arrays of triplet values across three spectral bands. Indeed, the UBV filter used in astronomical telescopes emulates strongly the sensitivity of the human eye to colour. Sharp changes in reflectance on a surface usually indicate object boundaries or edges. The basic philosophy behind image processing is to delineate objects in the world from the background based on finding their edges which have high contrast from the background. Human visual processing is highly robust to highly variable viewing conditions, significant levels of noise, highly variable degrees of occlusion of objects, and highly variable orientations. Humans cope by using extensive a priori knowledge and inferencing illustrating the necessity for model-based object recognition. A visual discovery algorithm to extract different image intensities from the background based on the human visual cortical receptive field model using multi-scale Gabor filters has been implemented [Burl & Lucchetti 2000]. This has the advantage of detecting visually different objects from the background without *a priori* models. It is particularly suited to microscopic imaging. They used Gabor filters in conjunction with centre-surround and corner-sensitive filters. Gabor filters are banpass filters which provide optimal resolution in frequency and space and conform the receptive fields of cortical cells. The 2 dimensional Gabor filter has the form [Xu et al 2004]:

$$G(x,y) = g(x,y)e^{-2\pi j[u_0(x-x_0)+v_0(y-y_0)]} \quad \text{where} \quad g(x,y) = \frac{1}{2\pi\sigma_x\sigma_y} e^{-(1/2)[(x-x_0)^2/\sigma_x^2+(y-y_0)^2/\sigma_y^2]}$$

(Gaussian function)

Alternatively, a polar form of the Fourier transform of the Gabor filter may be defined as:

$$G(x,y) = g(x,y)e^{-2\pi jF[\cos\theta(x-x_0)+\sin\theta(y-y_0)]} \quad \text{where} \quad g(x,y) = \frac{1}{2\pi\sigma^2} e^{-(1/2\sigma^2)[(x-x_0)^2+(y-y_0)^2]}$$

$F = \sqrt{u^2+v^2}$ =frequency of filter

$\theta = \tan^{-1}\left(\frac{v}{u}\right)$=orientation of filter

$\sigma = \frac{\sqrt{\ln 2}(2^B+1)}{\sqrt{2}\pi F(2^B-1)}$

B=frequency bandwidth (typically one octave)

The Sobel convolution mask invokes a centre-surround operation to make it sensitive to all edges. The centre-surround filter identified bright or dark localised regions that differ from their surroundings. The convolution mask for the Laplacian operator emphasises the central pixel at the expense of outer pixels which has a strong biological analogue. A centre-surround mask can locate grey-level boundaries to generate the edge map. The difference-of-Gaussian mask is an approximation of convolution with a Gaussian mask with a centre-surround mask (Laplacian of the Gaussian). The output of the centre-surround mask becomes positive and negative either side of the zero-crossings (light intensity boundaries).

Three dimensional information is derived from the disparity of corresponding regions in the two images from the two cameras. This angular disparity between the two images together with a known separation distance between the cameras enables the range computation. The procedure is common in nature and is the mode of distance estimation used by primates. Three steps are required for the measurement of stereo disparity [Marr & Poggio 1976]. First, a location on the scene must be selected from one image. Second, the same location must be identified in the other image. Third, the disparity between the two image points must be measured. This requires the identification of corresponding points in the images in the two cameras so that the images may be matched. This is the major problem in stereovision (the correspondence problem). The feature must have certain properties: it must be unique or, for multiple features, the disparity must vary smoothly across the object. It requires a given feature in one image to be registered with a corresponding feature in the other image such that they both correspond to the same feature in the 3D object (hence the name, the correspondence problem) [Marr & Poggio 1976, Ballard et al 1983]. Several constraints may be applicable. Corresponding points must share the same elevation y (equipolar constraint). A cooperative algorithm comprising a set of iterative difference equations can also solve the correspondence problem. Such an algorithm may be implemented as a multilayer artificial neural network perhaps as a special purpose board. The use of an artificial neural network mapping model is an effective way to provide the means of implementing parallel mutual constraint satisfaction. A neuron is assigned to each possible conjunction of an image element of one camera and an image element of the other camera. Inhibitory links can apply the uniqueness constraint so that line of sight units are suppressed while the continuity constraint of adjacent image points at similar depths may be implemented using excitatory links. Mutually consistent nodes would excite each other while incompatible nodes would inhibit each other.

Contrasts in images representative of objects are characterised by curvature, colinearity, symmetry, parallelism and cotermination [Biederman 1987]. Objects are segmented by regions of sharp concavity, especially at cusps where there are discontinuities in curvature. When gaps exist, humans assume continuity of curvature, colinearity, symmetry and cotermination, ie. humans fill in the gaps in contours during low level perception. These volumes may be based on generalised cylinders defined by a 2D curve that specifies a central axis and a cross sectional area or radius. There are 24 generalised conical "geons" from which all volumetric shapes can be built using 81 attachment relations defining their spatial relationships – two geons can construct over 10,000 objects and three geons can construct 306B objects (recognition-by-components). Generalised cylinders are based on translational invariance through a hierarchy of congruence relations. These primitive parts may be classified to form clusters which represent entire objects of possibly complex structure linking the primitive structures with set theoretic operators such as union, intersection and difference. It has been estimated that there are some 30,000 commonly experienced objects or categories of object in everyday hunter-gatherer, agricultural and urban life. This would require learning an average of 4-5 objects per day for 18 years. This is the peak rate of word acquisition by children at their peak between the ages of 2 to 6. There are certain natural objects which are not well modelled by geons but require fractal description.

The passive range pattern sensor system is an optical stereosystem with two lenses and one CCD imager which measure range of a scene projected onto the CCD [Takeno & Rembold 1996].

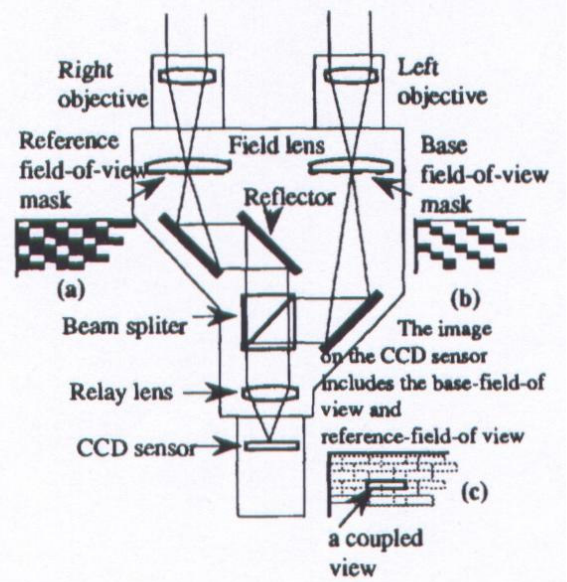


Fig 11-5 Optical structure of the passive range pattern sensor [from Takeno & Rembold 1996]

The two objective lenses are located in parallel with a baseline separation. A field lens, optical mask and reflector mirrors lie behind each objective lens followed by a single optical chain comprising a beam splitter, relay lens and CCD imager. The right and left optical masks are different – left mask is base FOV mask and right mask is reference FOV mask. Left and right masked images are projected onto the same CCD array through reflecting mirrors, beam splitter and relay lens. An image correlation function enables computation of range.

Neuromorphic vision sensors which emulate biological vision systems, particularly transduction and early vision processing. Such vision systems are based on the requirement to reduce computational loads in vision processing. CMOS imaging arrays based on active pixel sensors offer advantages over CCD cameras due to their low power consumption and ready integration with electronics but suffer from pattern noise and larger pixels [Etienne-Cummings 1996].

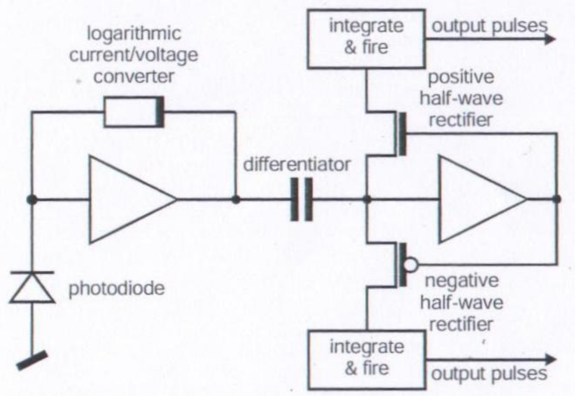
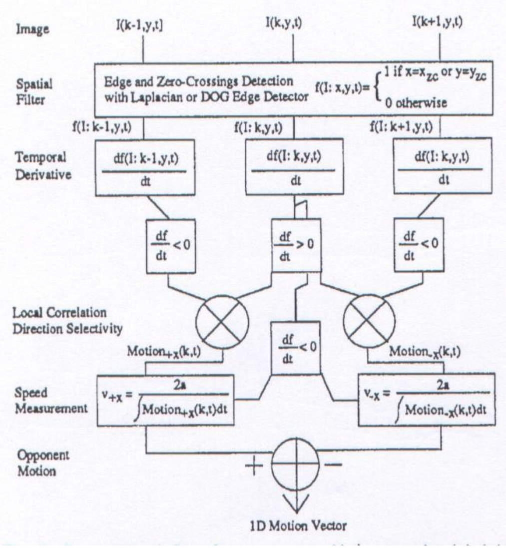
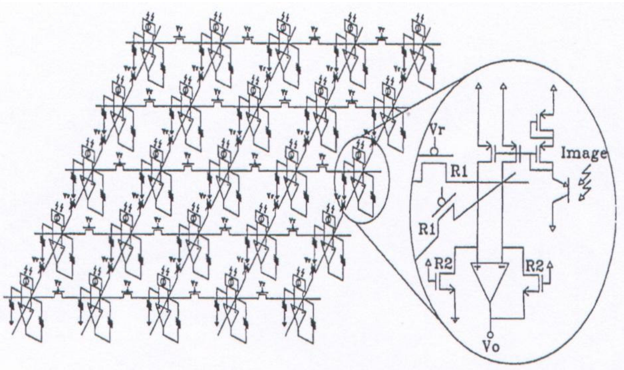


Fig 11-6 Single pixel schematic [from Landholt 2000]





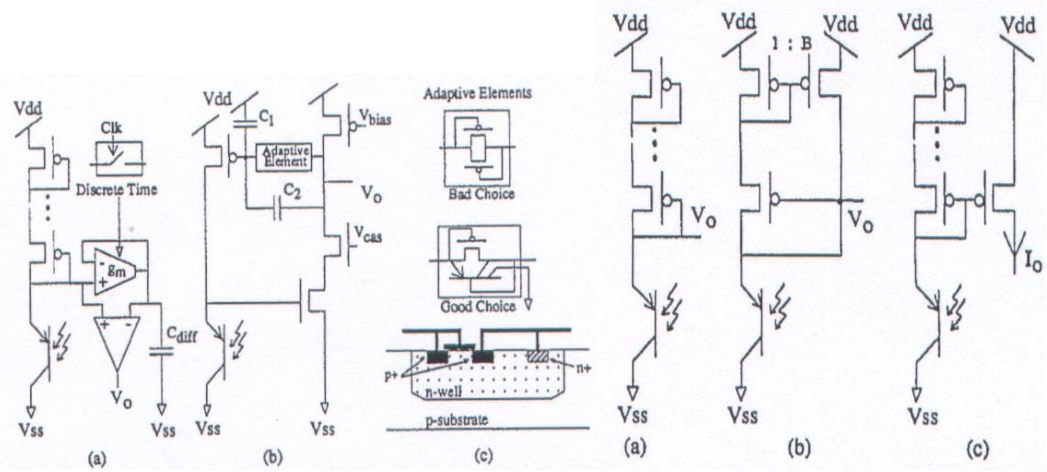


Fig 11-7 (a) Computational flow for neuromorphic/computational hybrid motion detection sensor – range compression, edge detection and motion detection; (b) Resistive array circuit used for edge detection; (c) Temporal adaptation circuits through temporal derivative, dynamic gain control and high adaptation time constants; (d)Range compression circuits where load transistors operate either in sunthreshold for logarithmic function or strong inversion [from Etienne-Cummings & Van der Spiegel 1996]

An artificial retina has been built which is 50 μm thick with a diameter of 3mm containing 7600 20x20 μm photodiodes in a rectangular array [Smye et al 2000]. Incident light generates a current due to the photovoltaic effect with an amplitude proportional to the intensity of light generating an image. The electric currents create a voltage in the ganglion cells. The silicon Mahowald retina provides the basis for emulation of the first stages of visual processing [Mead 1990].

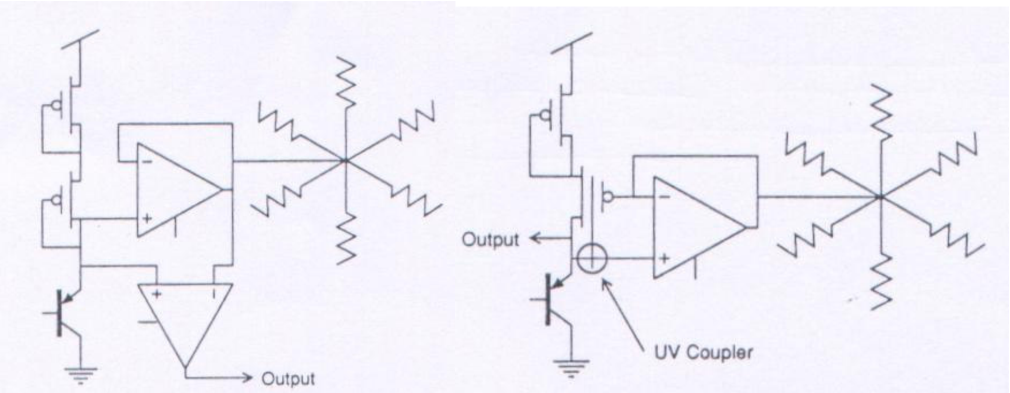


Fig 11-8 (a) Mahowald retina whose output is difference between potential of local receptor and restive network; (b)Maholwald retina adapted with ultraviolet light to correct for output variations among pixels [from Mead 1990]

Below the photoreceptors, a two dimensional network of cells coupled by resistive connections laterally spreads input information at the photoreceptors by applying a spatially weighted average of the input array. In the silicon retina, each node in the network is linked to its six neighbours with resistive elements to form a hexagonal array. Each photoreceptor acts as a voltage input that drives the corresponding node of the resistive network through a conductance. A transconductance amplifier implements a unidirectional conductance so that the photoreceptor acts as an effective voltage source. The silicon retina provides an automatic gain control so that it is sensitive to input changes. The brightness at each pixel is given by:

$$B = I - m\left(\frac{d^2I}{dx^2} + \frac{d^2I}{dy^2}\right)$$ where I=intensity=f(x,y)

m=constant

This gives an antagonistic centre-surround receptive field of the retina as a result of the interaction of the photoreceptors, resistive network and output amplifier. The output amplifier detects the voltage difference between centre intensity and the weighted average of the surrounding pixel intensities. This is equivalent to a Laplacian filter which may be approximated by a difference in Gaussians. The voltage stored in the capacitance of the resistive network represents both the temporally and spatially averaged output of the photoreceptors, weighted by an amount that decreases exponentially into the past. The Maholwald retina is sensitive to transistor offset voltages. To allow adaptation to applied ultraviolet radiation, the Mahowald retina may be modified. The application of ultraviolet radiation to a capacitor with a SiO_2 dielectric shunts the capacitor adapting the charge on a float gate. This effect may be exploited in an adaptive Mahowald retina. The output node is the emitter of the phototransistor. The current output is set by the local incident light intensity. Current into the output node is set by the weighted average light intensity in the neighbourhood computed by the resistive network. The difference between the two currents is converted into a voltage by the effective resistance of the output node. Small differences between centre and surround intensities are amplified into large output voltages. The retina operates over a high range of illumination. Catadioptric omnidirectional sensors comprising a camera and a conical mirror offer the potential for omnidirectional stereo with two catadioptric sensors in a vertical coaxial configuration [Spacek 2004]. They do not suffer from the distortion of curved cross-section fish eye lens cameras.

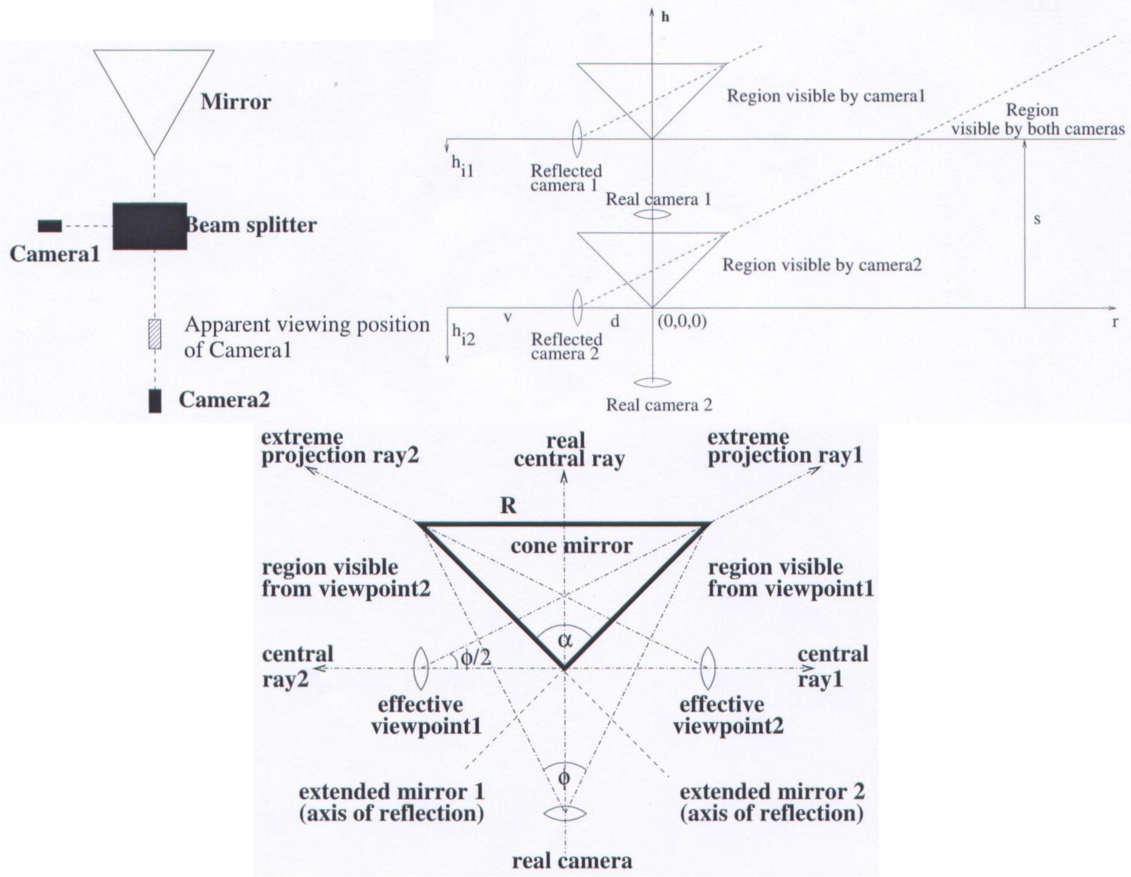
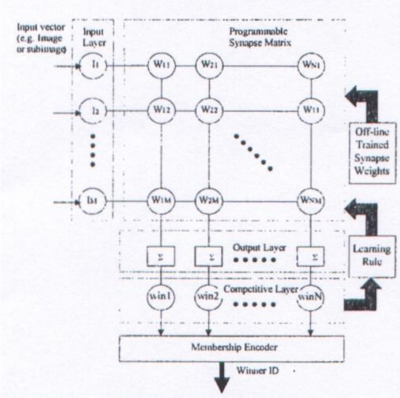


Fig 11-9 Catadioptric mirror (a) omindirectuional stereo using conical mirror and two cameras; (b) vertical binocular configuration; (c) catadioptric conical mirrir projection geometry [from Spacek 2004]

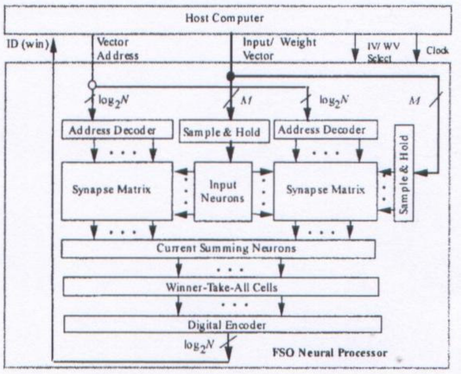
The appropriate camera distance:
$d = \left(\cot an \frac{\phi}{2} - 1\right)R$ where ϕ=field of view
R=radius of cone mirror

The triangulation for vertical stereopsis of given by radial diatance:
$r = \frac{vs}{h_2 - h_1} - d$ where $h_2 - h_1$ =vertical disparity
s=separation distance

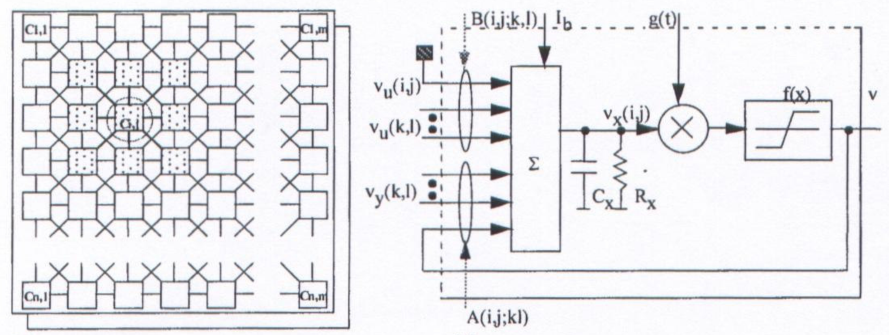
Neural networks based on the multilayer perceptron and Kalman filter gains to represent the learning parameter have been applied to remote sensing applications [Tzeng & Chen 1994]. The Kalman filter greatly increases the convergence rate of the usually slow backpropagation algorithm. In particular, neural networks similar to the neocognitron based on the Hubel-Weisel model of vision processing are particularly suited to object recognition in images [Cios & Shin 1995]. A 1024x1024 element CMOS active pixel sensor has been integrated with a programmable neural processor as an ultra-fast, smart sensor system-on-a-chip for space missions [Fang 2000]. The on-chip programmable cellular neural network is used as a parallel processor for vision processing such as feature extracton, motion detection, etc.



(a) A functional block diagram

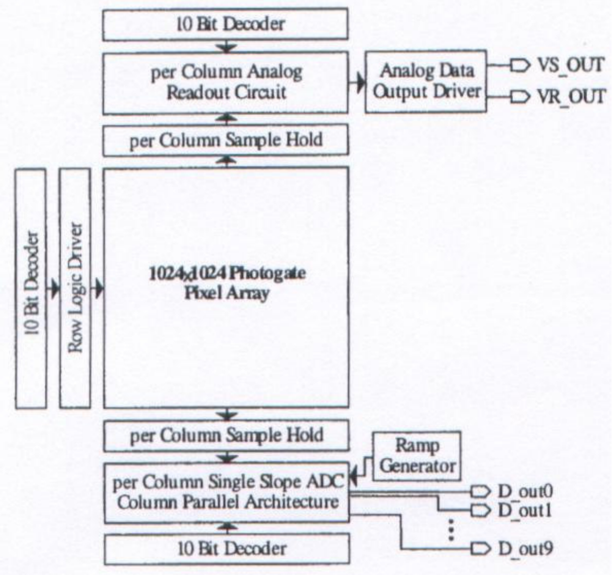


(b) A system-on-chip design



(a)

(b)



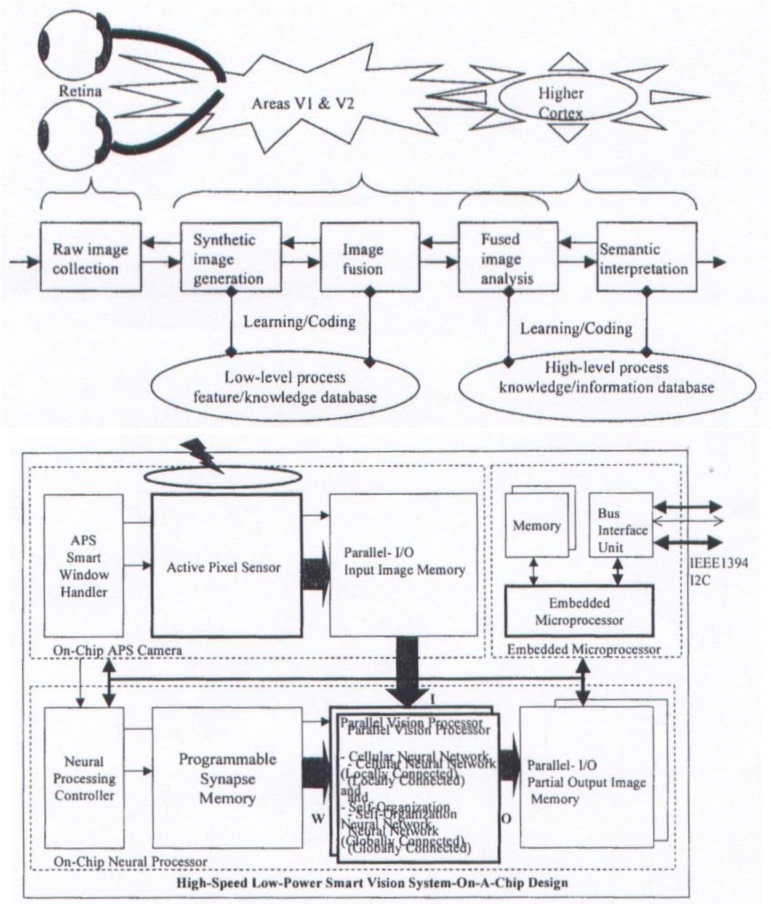
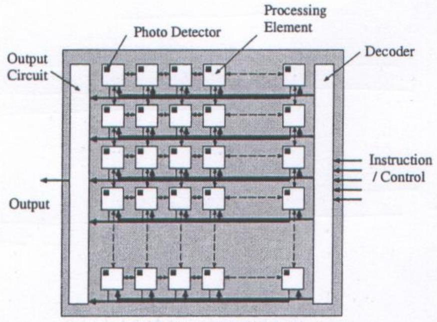
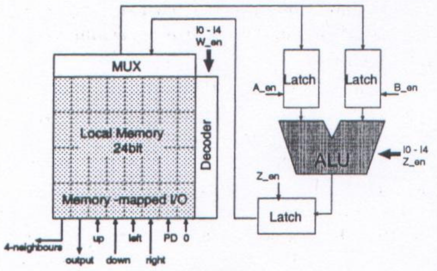


Fig 11-10 (a) Self-organising neural network chip; (b) Cellular neural network neural processor grid with functional block of each neuron; (c) CMOS APS prototype chip; (d) Smart vision processing model based on human visual processing; (e) Smart vision system-on-a-chip design [from Fang 2000]

A 1ms sample rate 16x16 2D array vision chip with sensorimotor fusion has been developed using a parallel processing array with photodetectors which can support high speed grasping using visual and force feedback [Ishikawa et al 2000]. Each processing element is directly connected to a photodetector, an output circuit, which are integrated in a single chip. Image signals from the photodetectors are ADC and transmitted in parallel to all processing elements and executed simultaneously (SIMD). This is transmitted to the output circuit. Each processing element has an ALU, a local RAM memory, and three registers.



(a) the whole chip



(b) PE

Fig 11-12 Vision chip architecture [from Ishikawa et al 2000]

The basic processes in early vision processing are smoothing, thresholding, edge detection, colouring and motion detection. From this, more global features such as edge/line orientations, regions and boundaries of objects can be determined within the visual cortex. Insect eyes have 360^o FOV and 3D location of objects in the FOV can be extracted from knowledge of which omadium is activated. Motion is also easy to extract by tracking the movement of the object across the FOV over the individual omadia. The difficulty lies in converting 2D sensing data into 3D controller signals for flight. Franceschini et al (1992) have developed a compund array of retinotopic visual motion sensors modelled on the housefly to steer a robotic vehicle. Visual motion detectors supprt navigation whilst avoiding obstacles in cluttered environments. A neural network provided data compression to output a small number of motor commands to drive the robot whilst avoiding obstacles. Neuromorphic sensors based on primate vision have foveated organisation of photoreceptors. The human eye is characterised by a large concentration of $\sim10^5$ optical fibres in $\pm0.5-1^o$ foveal region of the retina along the optic axis with high resolution. Away from the fovea the distribution of optical fibres becomes more diffuse and so of lower resolution through the majority of the visual field. This log-polar spatial layout of photoreceptors in universal in primates. In the periphery, the density of photoreceptors decreases logarithmically with eccentricity while the size of receptors increases – the number of pixels per radial displacement is constant. The central foveal regon has a small number of high density receptors which allows high scan rates with low numbers of output lines. This reduces the amount of data provides efficiency of information coding. Foveated vision is ideal for object tracking and time-to-impact computations – rotational motion corresponds to translation in the θ domain while divergent motion is transformned to translation in the r-domain. This is particularly useful in navigation and docking tasks. Their primary disadvantage is in the need for gaze control. In biological systems, there are two types of photoreceptor – rods are sensitive to very low light levels but have poor spatial, temporal and chromatic responses; cones have poor intensity sensitivity but have good spatial, temporal and chromatic responses. In artificial systems, this differentiation is not required as the quantum efficiency of Si photoreceptors – photodiodes, phototransistors, and CCDs (typically phototransistors due to their higher sensitivity) - is high. By using logarithmic compression, photoreceptors can maximise their sensitivity at the centre of the array. The phototransduction stage is enabled by a phototransistor and two diode-connected MOS transistors to convert five log units of intensity into an output of a range of 1 V. Current fed into the diode-connected pair generates a logarithmic gate-source potential difference. Negative feedback is used to control the photocurrent by reducing the number of electrons entering the base of the phototransistor. Alternatively, an inversion circuit exhibits a logarithmic relationship for very small currents, otherwise the output is square-log and approximately linear with increased intensity. Temporal adaptation may be implemented as patten noise cancellation which may be achieved through a simple time derivative operation similar to the cone adaptation through high pass filtering. Phototransdution, logarithmic compression and temporal adaptation can be achieved through a single circuit. A MOS/PNO hybrid was used to set the time constant of adaptation. Beyomd signal conditioning, edge detection comprises the first stage of image understanding by highlighting locations of discontinuities. The receptive fields of retinal ganglion cells use a difference-of-Gaussian or Laplacian-of-Gaussian edge detection scheme rather than a Hough transform. This may be implemented through regularisation with a resistive grid which requires only nearest neighbours connections. Motion detection has generally been achieved through gradient-based optic flow methods modelled on the fly's visual system. The idea is to measure the distance travelled by a stimulus in a delay interval by detecting peaks positions of time-averaged pixel correlation signals. Direction selectivity is obtained through injecting signals into a delay line when a pixel is active – the delay line performs the correlation by summing the signal with signals from previous pixels. The speed measurement may be based the transfer time between pixels. Orientation detection measures the angle of a line segment within the receptive field which may be achieved by weighting outputs through a first order Gabor function and summing them.

Active control of attention and the nonuniform resolution provides orders of magnitude improvement in image processing requirements, hence the element density of pixels of the CCD may be patterned after the human eye with high resolution FOV of 1-2$^{\mathrm{O}}$ and low peripheral resolution view of ~100$^{\mathrm{O}}$. Gaze shifting and gaze holding movements of the eye provide a means to rapidly aim this narrow FOV. Fast saccadic eye movements move the fovea between different targets in the visual field while active gaze control keeps the fovea on a specific target. The retina and the regions of the brain that control the 6 muscles of the eyeball in pairs corresponding to the 3 axes of rotation are connected in the optokinetic response neurons in a negative feedback loop. There is also a feedforward vestibulo-ocular reflex which uses the vestibular apparatus of the inner ear to detect movement of the head which responds much faster than the optokinetic feedback loop. A similar kind of control system architecture would be required for artificial gazing. Ballard (1991) advocated an animate vision paradigm based on this function. It would require an invariant object centred frame of reference (eg. the local inertial frame). Two cameras with foveated vision which are able to pan and tilt in synchronicity, each with independent saccading ability at 3 Hz and convergence control in the yaw axis could be used. A vestibular-ocular reflex with smooth pursuit of targets would provide robust static and moving target tracking. At any instant only a small number of features in the environment that are relevant to the particular task are registered and new features are incrementally registered only when required. This approach to vision would dramatically decrease the requirement for data transmission at any instant to the ground, but it is not clear if this approach would be suitable for teleoperation or even virtual reality methods as such gaze shifting and gaze holding would require tight slaving of the remote cameras to the teleoperator eye movements which average saccade movements 4-5 times per second – the remote camera inertia and articulation motors could not match those of the human eyeball. Active vision is required if visual fixation is to be maintained onto a moving target – human vision uses a number of mechanisms such as saccades, smooth pursuit and optokinetic reflex (OKR). A high resolution fovea with a centre-surround variation in resolution offers considerable reduction in image processing requirements. Saccade generation in the human brain involves the basal ganglia, posterior parietal cortex, visual cortex and superior colliculus.

Mammalian eye movements are characterised by saccades, smooth pursuit and gaze [Landolt 2000]. Saccades are fast ~1000°/s and frequent ~3 Hz jumps between fixation points to bring objects of interest in the view field into alignment with the high sensitivity fovea of the retina and to re-centre the eye when it strays to the edge of the orbit. Gaze is a target-holding smooth eye motion to stabilize the retinal image up to ~3s.

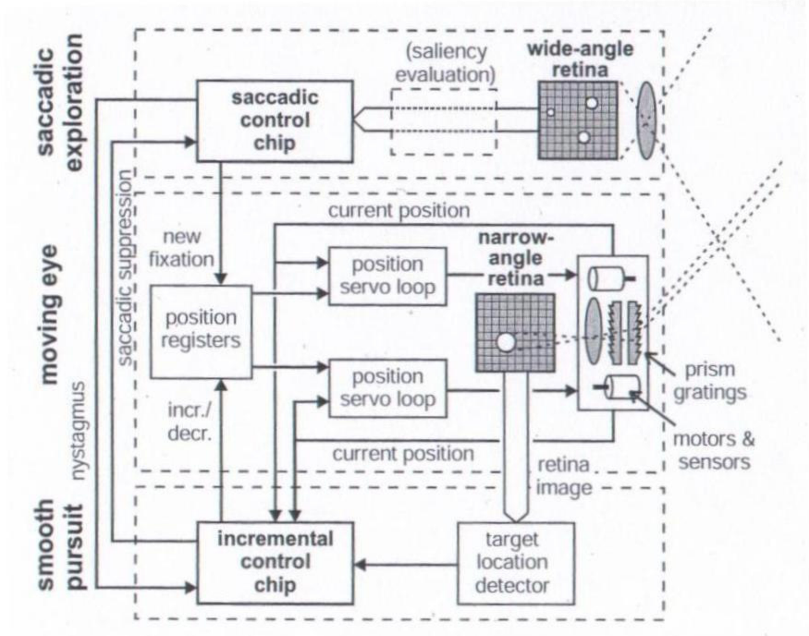


Fig 11-13 Oculomotor system architecture [from Landolt 2000]

The vestibular ocular reflex (VOR) is based on measurement of the rotation of the head by the vestibular system. VOR counteracts the effects of head movement by generating opposing eye movements up to ~500°/s to reduce retinal image slip. The optokinetic reflex (OKR) is similar but is controlled by the vision system. OKN counteracts for high image slipping up to 80°/s due to body movements. Smooth pursuit enables tracking of small moving objects up to 40°/s to keep it on the fovea. Even during fixed gaze however there are small involuntary drift/microsaccades ~arcminutes in amplitude and ~0.6s periods. This is required in order to maintain permanent vision – complete immobolisation of the eyeball causes objects to disappear. The eye detects intensity fluctuation over time measured by the retina rather than absolute intensity as the latter would yield visual artefacts such as blood vessel shadows, etc. Exploiting such small amplitude shifts of the optical axis in electronic imagers would enable increased resolution beyond the limits of photoreceptor spacing. Such a camera should be capable of generating saccades every 50-100 ms with an accuracy of 1° over a complete range of 60-90° (most camera FOV are ~40°). To rotate the visual axis, the retinal imager and focussing lens are fixed with a rotating microprism grating in front of the focussing lens. The complete oculomotor system comprises three modules – moving eye module which monitors rotation of imaging system using optical detectors and drives two motors, and a smooth pursuit and smooth pursuit modules. The smooth pursuit system computes the prism orientation required to centre the target on the retina. Corrective actions are computed by a topologically organised network of place cells connected with arrays of fuzzy logic AND gates. The saccadic exploration module is similar to the smooth pursuit system. It takes priority over the smooth pursuit system when invoked. Continuous oscillations ~pixel spacing and a scanning oscillation frequency >300 Hz offers the ideal characteristics. An array of logarithmic pixels whose threshold is set to fire on imaging a sharp edge provides high temporal bandwidth.

Adaptive vision-manipulator coordination requires the vision system to locate the end effector for each manipulator configuration and correlating joint variables and the camera orientation variables (pan, tilt and vergence) within the neural network connections [Blackburn & Nguyen 1994]. This involves storing joint angles and camera orientation angles when the camera is focussed on the end effector. The Kohonen self-organising map is the most appropriate neural network for such a task [Scheier & Lambrinos 1995].

Vision is essential for robots but is often ill-posed unless active vision is used to orient its actions within the environment. As an organism or robot moves, optic flow contains information about 2D surfaces defining objects and the motion of the agent. Visual servoing attempts to track moving objects particular through optic flow [Richards & Papanikolopoulos 1997]. Optic flow is retinal motion based on the projected relative motion of image pixels defined as a velocity vector at each pixel. Intensity is conserved in the image so brightness changes are purely due to motion. The brightness conservation is given by:

$$I(x, y, t) = I(x + v_x t, y + v_y t)$$

Neighbouring points move at the same velocity:

$\frac{dI}{dt} = \frac{\partial I}{\partial x}\frac{dx}{dt} + \frac{\partial I}{\partial y}\frac{dy}{dt} + \frac{\partial I}{\partial t} = 0$ where u=dx/dt, v=dy/dt

Only the normal velocity component can be solved as there are two unknowns and one equation (aperture problem). By computing the temporal derivative and thresholding it to filter out noise:

$$\frac{dI(x,y,t)}{dt} \approx \frac{I(x,y,t) - I(x,y,t-\delta t)}{\delta t}$$

Zero crossings of the second derivative of the Gaussian filter as an edge locator.
Linear least squares estimate fit of normal flow vectors to a constant velocity requires minimisation of the function:

$\sum w(x)\left(\nabla I(x).v + \frac{\partial I(x)}{\partial t}\right)^2$ where w(x)=weights which emphasise central pixels

The focus of expansion (FOE) defines points on the motion field from which the flow vectors appear to originate. The focus of contraction (FOC) defines the points where the flow vectors disappear. They are both in the field of view for pure translation but lie outside the field of view for pure rotation. Mixed rotation and translation cause relative positions of FOE and FOC to vary. The focus of expansion which lies at the centre of the radial flow pattern determines the direction of movement. Time to contact with a surface is given by the rate of expansion $\tau = \frac{\theta}{\dot{\theta}}$ where θ=visual angle between point on surface and focus of expansion, $\dot{\theta}$=radial optic flow=$\frac{v.\sin\theta}{d}$ during pure translation where d=distance to point P. To maintain ambient orientation, eg. hovering, optic flow should be minimised such that:

Upthrust, $\Delta U = \left(\frac{k}{c}\right)\Delta w_v$ where k=drag
c=optic scaling
w_v=vertical optic flow

$\Delta(F_L - F_R) = \left(\frac{k}{c}\right)\Delta w_h$ where F=forward thrust

w_h=horizontal optic flow

The balancing strategy control law defines the centring response from optic flow across the whole FOV [Duchon et al 1997]:

$$\Delta(F_L - F_R) = K\left(\frac{\sum w_L - \sum w_R}{\sum w_L + \sum w_R}\right)$$

Motion parallax indicates that when the agent is translating, closer objects generate faster motion across the retina than objects further away. In addition, closer objects take up more of the FOV. The agent turns away from the side of greater flow. In order to make soft docking with the target, a form of PD control may be used:

$$\Delta(F_L + F_R) = K(\dot{\tau} + c) \text{ where c=0.5}$$

The flight trajectory of flies is characterised by straight line flight interspersed by rapid direction changes during which velocity drops (saccades) [Dickinson et al 2000]. Each saccade is invoked by visually mediated collision avoidance reflexes. Insects have immobile eyes with fixed focus optics and have small baseline limiting their visual acuity. In the housefly, over half of its 350,000 neurons are devoted to vision processing. Each compound eye of *Drosophila* comprises around 700 omatidia (equivalent to a 26 x 26 pixel mutlilens array). The blowfly *Calliphora erythrocephala* has 6000 lenses beneath which is a cluster of 8 omatidia (equivalent to a 77 x 77 pixel array). Six of the 8 photoreceptors are arranged in a hexagonal array and implement neural superposition, each providing a 1.1-1.3° angular resolution (compared to 0.008° resolution of the human fovea). Optical flow is defined by the angular speed induced by an object at a distance d such that a nearer object induces a smaller angular velocity: $w = \frac{v}{d}\sin\phi$.

Viollet & Franeschini (2000) model the insect lens-photoreceptor system as a Gaussian function such that its angular sensitivity is given by:

$$S(\phi) = \left(\frac{abs(G_i(\phi) - s_0) + (G_i(\phi) - s_0)}{2}\right) \text{ where } G_i(\phi) = e^{-\phi^2/2\sigma^2}$$

Angular half-width is given by: $\Delta\rho = 2\sigma\left(2\ln\left(\frac{2}{1+s_0}\right)\right)^{1/2}$

Photoreceptor output is given by:

$$R_i(t) = \int_{-L_v}^{L_v} I(\phi)S(\phi).d\phi \text{ where } L_v = \text{angular width at half height}$$

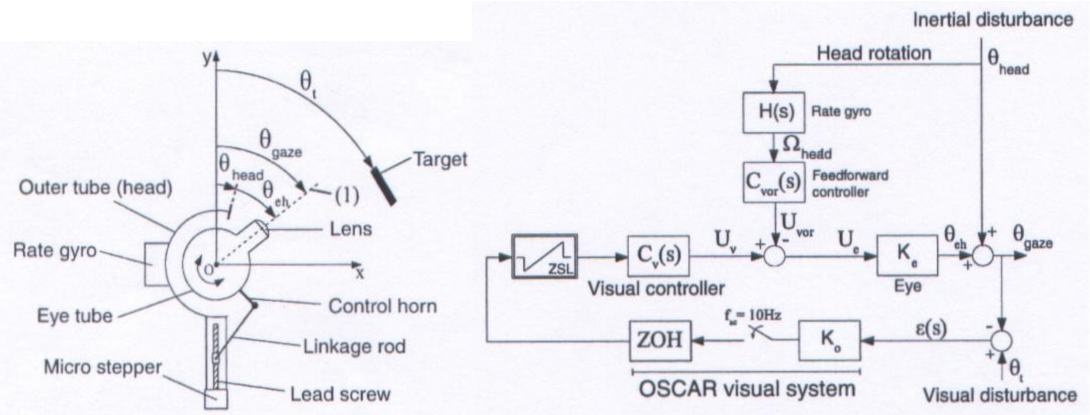


Fig 11-14 (a) Eye-in-head mechanism; (b) Gaze control system [from Viollet & Franceschini 2005]

Photoreceptors in the retina detect light intensity and converge onto optic ganglion cells, each focussing a 5° sector. Photoreceptors output to lamina cells of the first optic ganglion which have a high pass response to emphasise transient temporal change but are not motion-specific. They output to the second optical ganglion (medulla) which provides local measures of motion. These direction-selective motion estimates converge and are integrated by the 50-60 tangential cells in the third optical ganglion (lobular plate) which act as matched filters for optic flow patterns along particular axes of translation or rotation. It is these cells which generate compensatory optomotor reflexes to compensate for horizontal, vertical and rotational deviations from straight-line motion. These computations within the fly can occur within 30 ms. The velocity at which an image moves across the retina depends on the distance of the object and such optic flow on the insect's left and right sides are balanced. This may be emulated by a 2D array of Hassenstein-Reichardt elementary motion detectors within the fly's optic lobes which use a delay and correlation algorithm between one photoreceptor and a delayed signal from another photoreceptor to compute a directional velocity response (local optic flow velocity) [Harrison 2002]. Image intensity may be given by:

$I(x,t) = I + \Delta I \sin(2\pi f_s (x + vt))$ where I=intensity

f_s=spatial frequency
v=image velocity

$= I + \Delta I \sin((w_t t + w_s x))$ where $w_t = 2\pi f_t$ =temporal frequency

The dc response is pre-filtered. If two photoreceptors are separated by ϕ, the photoreceptor signals are given by:

$p_{1,2}(t) =| H(w_t) | \Delta I \sin(w_t t \pm w_s \frac{\phi}{2})$ where $H(w_t) = \frac{Kjw_t\tau_H}{(jw_t\tau_H = 1)(jw_t\tau_P + 1)}$

=photoreceptor temporal freq response

τ_H = time constant of high pass filter

Delay required by motion detector is provided by phase lag within a low-pass filter:

$$l_{1,2} = \frac{|H(w_t)|\Delta I}{\sqrt{\tau^2 w_t^2 + 1}} \sin(w_t t \pm w_s \frac{\phi}{2} - \tan^{-1} \tau w_t)$$

Correlation involves multiplying phase lagged signal with adjacent non-delayed signal:

$m_{1,2}(t) = G(\cos(w_s \phi - P) \pm \cos(2w_t t - P))$ where $G = \frac{(|H(w_t)|\Delta I)^2}{2\sqrt{\tau^2 w_t^2 + 1}}$

$P = \tan^{-1} \tau w_t$

The final output is:

$$o(t) = (\Delta I)^2 \mid H(w_t) \mid^2 \frac{\tau w_t}{\tau^2 w_t^2 + 1} \sin \phi w_s$$

The dependency on velocity is given by:

$$o(t) = (\Delta I)^2 \mid H(w_s v) \mid^2 \frac{\tau w_s v}{\tau^2 w_s^2 v^2 + 1} \sin \phi w_s$$

The Hassenstein-Reichardt motion detector has been implemented in VLSI hardware through a four-transistor photodetector with source follower and temporal high pass filter to remove the dc component, a temporal low pass filter to impose the delay, and a Gilbert multiplier to correlate the delayed and non-delayed signals.

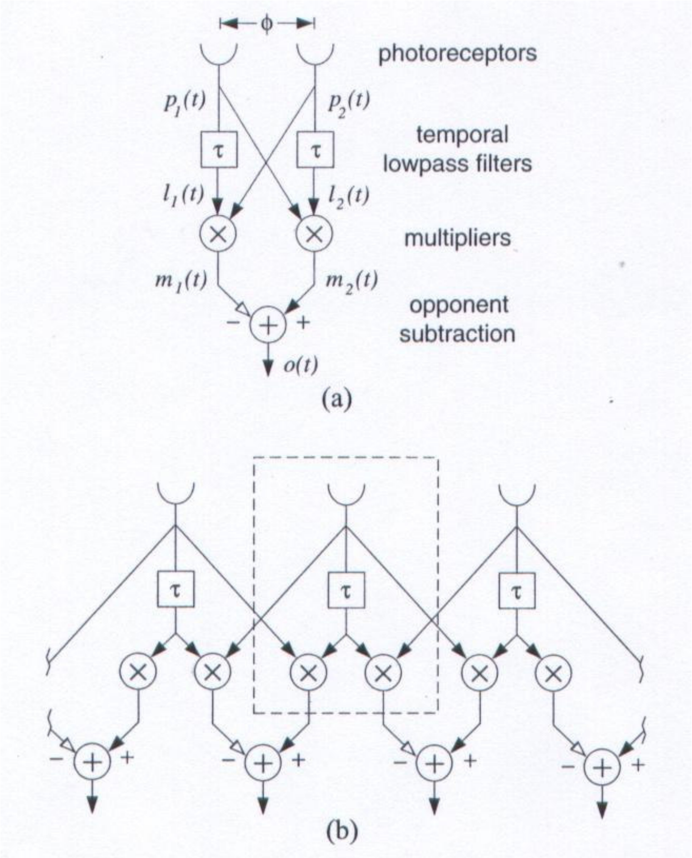


Fig 11-15 Reichardt motion detector: (a) signal from one photoreceptor is correlated with delayed signal from adjacent photoreceptor; (b) 1D array of Reichardt motion detectors [from Harrison et al 2002]

The output is given by:

$I_{out} = \frac{I_b}{2} + \frac{\kappa^2 I_b}{8U_T^2}(V_1 - V_a)(V_2 - V_b)$ where I_b = bias current

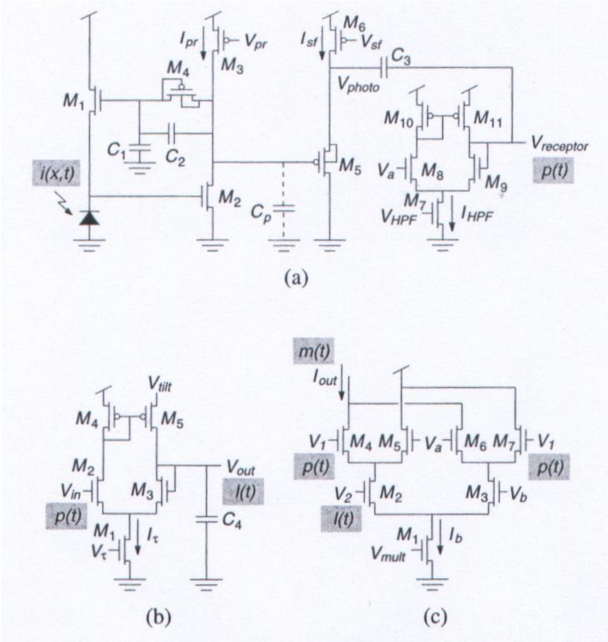


Fig 11-16 Voltage mode EMD subcircuits (a) adaptive photoreceptor; (b) temporal lowpass filter (c) Gilbert multiplier [from Harrison et al 2002]

Bees balance the seeds of image motion on the two eyes to navigate – a lower image speed on one eye causes the bee to move towards that side [Srinivasan 2000]. Speed control is implemented by keeping the sum of the two image speeds constant. During landing, expansion of the image surface is used to control deceleration and trigger leg extension for contact. The rate of image expansion is used to compute the time to contact. The average angle of descent is ~28°. Horizontal speed is approximately proportional to height. Angular velocity of the image of the surface, $w = \frac{v_f(t)}{h(t)}$ ~500°/s where $v_f(t)$ = horizontal velocity

h(t) = height

Bees control their forward flight speed to hold image velocity of the ground constant and couple the descent speed to forward speed. Descent speed decreases with forward speed becoming zero at touchdown.

Descent speed, $v_d(t) = -\frac{dh(t)}{dt} = K.v_f(t)$

Hence, $Kwh(t) + \frac{dh(t)}{dt} = 0$ yielding $h(t) = h(t_0)e^{-wK(t-t_0)}$ where $h(t_0)$ = height at time t_0.

Forward flight speed varies similarly: $v_f(t) = wh(t_0)e^{wK(t-t_0)}$

Cumulative horizontal distance is given by:

$$H = \int_{t_0}^{t} v_f(t)dt = \int_{t_0}^{t} wh(t_0)e^{-wK(t-t_0)} = \frac{h(t_0)}{K}\left(1 - e^{-wK(t-t_0)}\right)$$

This strategy ensures that both forward speed and descent speed reduce to zero at touchdown [Srinivasan 2000].

Optical flow field methods provide the means for motion-detection [Giaccone 1998]. As a robotic rover is a moving vehicle, detection of motion allows the determination of the motion of the vehicle. Optical flow methods generate a vector field representing the motion of the pixels of an image. Associated with each pixel is a velocity vector and the vector field of all pixels of the image form the optical flowfield. Pre-smoothing the images with a Gaussian filter to reduce aliasing introiduces blurring. Continuity of the motion field is ensured by applying the constant brightness constraint which states that a moving pixel's brightness is constant, or at least almost constant: $I_t(x) - I_{t-1}(x) + \nabla I^T u_t(x) = \varepsilon$ where ε is a small threshold. It is assumed that apparent 2D motion of objects in an amage sequence is represented as an affine model:

$$u(x) = \begin{pmatrix} u(x) \\ v(x) \end{pmatrix} = \begin{pmatrix} a_0 + a_1 x + a_2 y \\ a_3 + a_4 x + a_5 y \end{pmatrix} = \begin{pmatrix} 1 & x & y & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 & x & y \end{pmatrix} \begin{pmatrix} a_0 \\ \dots \\ a_5 \end{pmatrix}$$

The parameters a are coefficients of affine functions of pixel coordinates. This equation is then embedded into the constant brightness constraint. It is not clear if motion-detection is necessary as the speed of the rover will be low, though it does add further capabilities in support of autonomous navigation.

Pan/tilt of the camera is defined by the transformation of the lens centre with respect to the reference frame formed by the intersecting x (tilt) and y (pan) axes of rotation for arbitrary inclination angle θ [Murray & Basu 1994]:

$$P_{ref} = \begin{pmatrix} 1 & 0 & 0 & \rho_x \\ 0 & c\theta & -s\theta & c\theta\rho_y - s\theta\rho_z \\ 0 & s\theta & c\theta & s\theta\rho_y + c\theta\rho_z \\ 0 & 0 & 0 & 1 \end{pmatrix} P_{lens}$$

For initial inclination of θ,, Kanatani's relation describes the camera pan and tilt angles α and γ respectively:

$$x_{t-1} = f \frac{x_t + \alpha \sin\theta y_t + f\alpha\cos\theta}{-\alpha\cos\theta x_t + \gamma y_t + f}$$

$$y_{t-1} = f \frac{-\alpha \sin\theta x_t + y_t - f\gamma}{-\alpha\cos\theta x_t + \gamma y_t + f}$$ where f=focal length

The vestibulo-ocular reflex (VOR) stabilises human gaze to keep the retinal image steady and utilises inertial sensors to measure angular head velocity while the vision sensor measures retinal angular position sensor [Viollet & Franceschini 2005]. The gaze controller involves feedback based on retinal position error and a feedforward signal based on angular head velocity. The feedforward control system triggers the rapid VOR which in humans has a latency of only 10 ms with head rotation frequencies of 4-6 Hz. The artificial VOR gaze control system was capable of frequencies of ~1 Hz.

Bats are nocturnal mammals who use echolocation to navigate and locate prey. They use ultrasonic high frequency signals ~8-215 kHz (human high frequency limit is 20 kHz) as pulses of ~1-50 ms in duration (average 1-10 ms) separated by ~5-100 ms. The sounds are generated in the bat's larynx and emitted through the mouth or nose. When the sound pulse encounters an obstacle, it rebounds as an echo that the bat detects with its ears, thereby allowing the detection of range (up to 9m maximum) based on the time delay between emission and detection. Differences in the received signal strength between the two large ears gives bearing. Bat echolocation intensities can be as high as 110 dB 10cm front the bats face. Whilst emitting such high intensity sounds, they dampen the movement of the middle ear bones – indeed, in the little brown bat *Myotis lucifugus*, they are disconnected. In the bat echolocating system, the bat attenuates signals from its own vocalisations by contracting its middle ear prior to vocalisation, and neurally attenuates detected vocalisations its brainstem auditory pathways. Most bats emit a specific frequency profile, eg. little big brown bat begins at a high 100 kHz for high resolution and then drops to 40 kHz for greater range. Bats can detect Doppler shifts in received signals when computing the distances to moving target, even detect insect wing fluttering. Odontocetes (toothed whales) use sonar echolocation for navigation and chasing prey. Sound pulses ~1-5 kHz are sent out through the water and the returning echo is received by the ears and analysed by the brain for distance and bearing. Sound is produced in ducts that run through the spherical melon on top of the skull between the snout and the eyes. The melon is filled with fatty material which acts as a focussing lens for sound into a narrow beam. The sperm whale is an odontocete whose large head is primarily occupied by oil-filled structures, air-filled nasal ducts together with the fatty melon – the spermaceti organ – to generate high-energy sonar. The airflow is channel by the nasal ducts causing mechanical vibration and the emission of high frequency sound which in turn are transmitted to the surrounding water through the oil filled structures. The air gets recirculated. The primary role of cetacean sonar is for echolocation of prey. For underwater sonar, frequencies have to be below 10 kHz for sufficient range (eg. whale sonar clicks peak at 1-5 kHz) which offer resolutions up to 0.4 m. The spermaceti complex focuses the sonar beam into a narrow beam. Sound intensity of odontocetes' clicks ~140-180 dB, and can reach as high as 265 dB which incapacitate their prey. The obvious technological examples of such active sensing techniques include sonar (not operable in space), radar and lidar.

11.4. TACTILE SENSING

It is not always straightforward to differentiate sensing from actuation – in biological systems, there exist neurones which are both sensory and neurosecretory and endocrine cells which have smart detectors which both regulate autonomoys fubctions using local processing [Wenning 1999]. The obvious example in relation to robotics is proprioception which form an integral part of motor pattern generation. There are three different modalities to the somatosensory system:

(i) discriminative touch to detect pressure, vibration and texture based on four types of skin receptors: Meissner's corpuscles, Pacinian corpuscles (both rapidly adapting to detect differences), Merkel's disks, and Ruffini ending (both slowly adapting to detect absolute pressure)
(ii) pain and temperature sensing relies on free nerve endings which detect temperature changes and substances released by damaged tissue (prostglandins, histamine and substance P)
(iii) proprioceptive sensing within muscles and joints by muscle spindles which measure muscle stretch (both rapidly and slowly adapting types) and Golgi tendon organs to measure muscle tension

The receptors are also classified according to sensory axon conduction velocity which is proportional to the axonal diameters. The largest and fastest axons are Aα (characteristic of proprioceptive receptors), followed by Aβ (characteristic of all discriminative touch receptors), then Aδ axons (characteristic of fast sharp pain receptors), and finally, unmyelinated C axons (characteristic of temperature receptors and slow dull pain receptors). Proprioceptive receptors ascend through the spinocerebellar tract to the cerebellum but some fibres diverge to follow the medial lemniscus to the cortex. Pain and temperature receptors ascend through the spinothalamic tract through the brainstem to the thalamus. The central nervous system produces its own neurotransmitter peptides which reduce pain – endorphins, enkephalins and dynorphins – and possesses distributed opiate receptors which respond to them. Somatosensory pathways from the face enter the brainstem through the trigeminal nerve to the pons.

Although scorpions possess the most light-sensitive eyes, they generally locate their prey by detecting air movement using sensory hairs (trichobothria) similar to spiders. They are relatively inactive most of the time but capable of rapid movement sporadically. Their low metabolic rate makes them suitable to deserts. Touch sensing is an essential complement to vision which is less useful at the 0.01-1mm ranges though human visual acuity is capable of perceiving ~3arcsec [Holliday 1993]. The posterior parietal cortex in the primate brain integrates visual and sensory-motor data – it plans arm movements to targets in space. By inserting multi-electrode arrays into the posterior parietal cortex, neural signals can be detected and sent to a robot arm, thereby providing the basis for direct neural-electronic interfacing. DERA's cognitive cockpit is a programme to allow pilots to control the flight of an aircraft by looking at the icons on a computer screen which generates specific brain wave patterns. To incorporate controllable prosthetics requires incorporation into the brain's body map which in turn requires feedback from those prosthetics to the brain. However, neural implantation is currently invasive making its utility limited. Touch is of primary importance possibly more important than vision for fine manipulation and may be regarded as a form of refined force sensing [Paul 1987]. Exploratory groping of surfaces with a tactile sensor is an efficient way of determining 3D structure and vision can be employed to provide guidance to the touch sensor. Indeed, blind people use touch extensively and can survive adequately in the world - it is debatable whether a man devoid of touch could do so well. Touch is an active, exploratory process in which sensing and actuation are intimately linked such that the actuation process through movement of the hand and fingers define the sensory data directly. Taction does not suffer from inoperability in darkness, or from problems due to shadows, lighting constraints, colour or obscuration though it does suffer from restricted views of the object. There are four basic human skin sensations of pressure, texture, temperature and pain. The human hand has 20,000 tactile nerve sensors, each finger possessing around 2000 tactile receptors each. Slip sensing is also required. Slippage can occur due to gravitational loading (absent in space) or from manipulating objects with high inertias. Slip can be prevented by increasing normal gripping force before the tangential force reaches the static friction (stiction) between the object and the end effector so that the normal force exceeds stiction.

Ayers et al (1998) have developed a number of biomimetic sensors for a robotic lobster. Crustacean exteroreceptive sensors are modified hair cells. A cantilever system modelling a hair provides the basis for such sensing. When the hair is normal to the substrate surface, applied forces cause the hair to deflect. Outer cantilever beams are mechanically connected to the central beam (hair), so when the hair is deflected, the outer beams contact the counter electrode on the substrate creating a short circuit. This gives an on-off signal. The threshold is determined by the beam stiffness and the cantilever length. A tilt sensor can be fabricated similarly with a weight at the end of the hair (similar to vestibular hair cells in the statocyst).

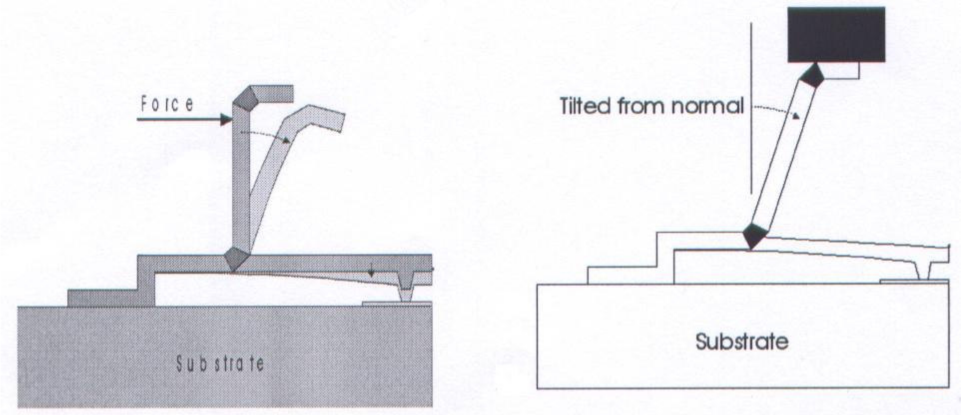


Fig 11-17 MEMS-based hair cells to measure (a) fluid flow (b) inclination [from Ayers et al 1998]

An 8-taxel tactile sensor chip covered with silicone rubber has been developed for measuring force distribution on its surface through pressure-sensitive capacitance which includes on-chip switched capacitors for signal amplification [Leineweber et al 2000]. The silicone rubber – Elastocil^R RT601 - is stable to most chemicals with stable elastic properties (E=7x10 N/m^2) between –50-180^{o}C, and self-healing. The pressure sensors were constructed from a polysilicon membrane top plate and a silicon substrate bottom plate separated by an 80 μm diameter 800 nm high cavity. Each 240x240 μm^2 taxel comprised two sensor capacitors and two reference capacitors (with thicker less sensitive membrane) giving a sensitivity of 1.5 V/bar and a maximum position error computation of an object exerting pressure of 2.4 μm. It uses a 6000x400 μm^2 two stage SC circuit to generate an analogue voltage from the pressure capacitors:

$$V_{out2} = V_{\min} + \left(\frac{C_2}{C_1}\right)(V_{out1} - V_{cal} - V_{off}) \quad \text{where } V_{out1} = V_{\min} - \left(\frac{C_R}{C_S}\right)(V_{\max} - V_{\min})$$

C_R, C_S = taxel capacitances
V_{max}, V_{min} = reference voltages = 4.5 V and 0.5 V
V_{cal} = input voltage to cancel taxel offset voltages

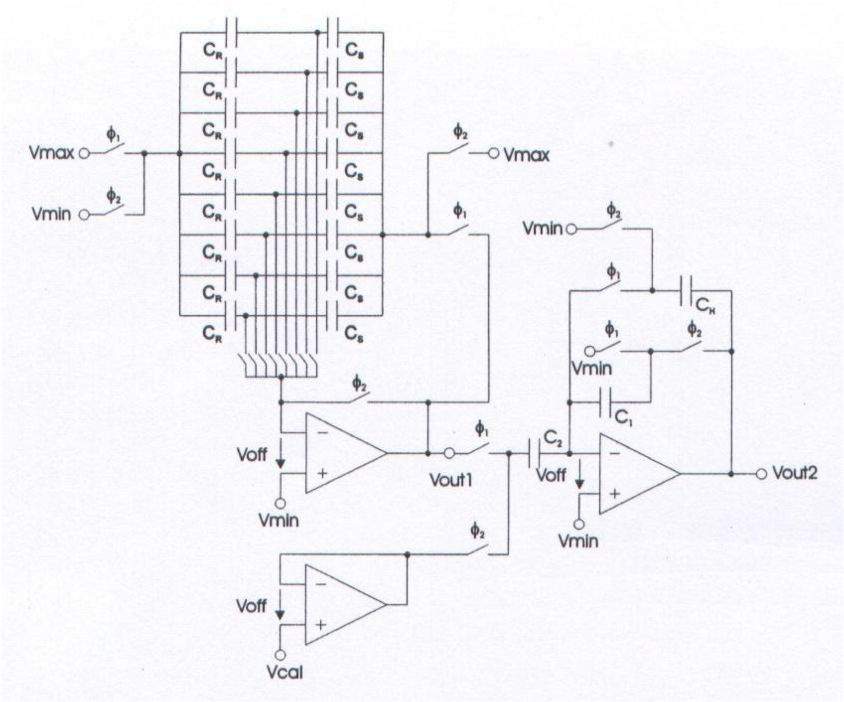


Fig 11-18 SC circuit [from Leineweber et al 2000]

The tactile sensor model output from z=0 plane is given by:

$$S = \frac{1}{ab}\int_{-a/2}^{a/2}\int_{-b/2}^{b/2}\sigma_z(x,y,z).dxdy \quad \text{where } \sigma_z(\rho,z) = -\frac{3P}{2\pi}\frac{z^3}{(\rho^2+z^2)^{5/2}} \text{ =elastic stress}$$

$$\rho = \sqrt{x^2+y^2}$$

a,b=taxel dimensions in x,y directions
P=load

Depth of penetration, $\delta = \frac{A^2}{R}$ where R=radius of contact

$$A = \sqrt[3]{\frac{3PR(1-v^2)}{4E}}$$

E=elastic modulus
v=Poisson' s ratio=0.5 for silicone rubber

$$P = \frac{4}{3}\delta^{3/2}R^{1/2}\,\frac{E}{(1-v^2)}$$

The maximum error due to noise is given by the Gaussian function: $g(x) = -2A\frac{x}{w^2}e^{-(x-x_0)^2/w^2}$

Tactile sensors may take the form of an "artificial skin" distributed as arrays of pressure-sensitive pads over the robot links on a thin, flexible compliant substrate for continuous tactile sensing in all directions. The transducers must be durable and wear-resistant particularly to slip friction. Harmon (1982) discussed the most desirable properties for touch sensors. Fast transduction and response times are requires ~1-10ms compared with human reaction times of ~200ms. Resolution requires 1-2mm spacing between sensors corresponding to 5x10 to 10x20 elementary points for a finger tip - this brackets the human fingertip characteristic of 10x15 points. The dynamic range required is from 1g to 1kg with a sensitivity of 1g. Hysteresis should be negligible. Presently available arrays have good spatial resolution but do not provide all of the other requirements. Resistive and conductive elastomer materials are promising if the dynamic range can be increased and hysteresis reduced. They are cheap, heat resistant and easily fabricated. One example is the use of carbon fibre inserted into orthogonal silicone rubber sheets. The carbon fibre responds to pressure by decreased electrical resistance while the silicone rubber conducts current in response to pressure according to decreased resistance at the strip interfaces. Piezoelectric materials are insulators which produce charges on their surface when mechanically deformed, a property determined by the piezoelectric coefficient $\left(\Delta l/l\right)\left(\Delta E/E\right)$, eg. quartz has a piezoelectric coefficient of 2x10^{-12} m/V. Lead titanate and lead zirconate have much higher values. The crystal deformation produces an EMF which can be measured in conjunction with a high gain DC amplifier with high input impedance. Piezoelectric polymers are subject to electric charge generation in proportion to the displacement resulting from an applied force such that integration of the current value gives the force value. Polymeric piezoelectric film transduction has great potential with high signal-to-noise ratios and good flexibility but are again fragile. An example of this technology is the use of polyvinylidene flouride (PVF_2). When stretched to 4 times its natural length it achieves a piezoelectric state. Piezoresistive transduction which also undergoes decreased electrical resistance under pressure also has great potential but the sensors tend to be rigid, stiff and slippery. However they are robust to high temperatures ~1100^{O}F and offer low hysteresis. Magnetoresistive materials (eg. Ni-based metals like Rumalloy 81/19 Ni-Fe) respond to external forces by altered resistance due to altered magnetic fields. Tactile sensors have a tendency to suffer from wear and tear but for space applications wear and tear is not the constraint that it is in industrial applications. Thermoplastic polyurethanes have excellent elastomeric properties suitable for robotic skins. Polyhydroxyethyl methacrylate hydrogel have excellent pH responsivity for use as artificial muscle. One option is to adopt bioengineered skins , eg. integra artificial skin with an outer polysiloxane polymer layer for mechanical strength and inner collagen fibre network layer [Kirsner et al 1998, Angelova & Hunkeler 1999].

11.5. HAIR TRANSDUCTION

In normal hearing, sound waves generate vibrations of the tympanic membrane which are transferred through three bones to the fluid-filled cochlea. These vibrations are transmitted as pressure differences in the cochlea fluid which causes deformation of the basilar membrane which contains around 16,000 hair cells. Hair cell movement triggers action potentials in the auditory neurons. Frequency is encoded as position along the cochlea. The cochlea is the main hearing organ in vertebrates comprised of a coiled canal around a central axis. The organ of Corti lies within the cochlea duct. Reptiles possess one type of hair cell while mammals possess two (inner and outer hair cells) within the organ of Corti. In mammals, the organ of Corti is divided into two partitions, on one side are three rows of outer hair cells and on the other a single row of inner hair cells. Inner hair cells are the primary sensory cells while outer hair cells are contractile for biomechanical gain control. The cell bodies of inner hair cells are flask-shaped whilst those of the outer hair cells are cylindrical. Sound stimuli is detected in the cochlea by vibration of the basilar membrane. Low frequencies are detected at the apex and the higher frequencies towards the base of the cochlea. This causes vibration of hair bundles emanating from sensory hair cells relative to the tectorial membrane. The hair bundle is comprised 20-300 sterecilia organised in rows of increasing height with fine tip links interconnecting the stereocilia. The outer hair cell stereocilia are smaller and more numerous than inner hair cell stereocilia and both are comprised of densely packed actin filaments. When the hair bundle tip bends towards the tallest hair, this activates mechanotransducer ion channels and generates an electrical signal. A displacement of 100 nm at the tip of the hair bundle is sufficient to open the transducer channel. The compliance of the hair bundle determines the amount of deflection to a given force. Active compliance for adaptation is provided by tension in the tip link adjusted by moving its upper attachment point along the side of the stereocilium. Calcium ion influx through the transducer channel causes the myosin molecules to detach from the actin core of the stereocilium thereby causing the link's attachment to slip. The hair bundle thus behaves as a highly tuned mechanical resonator such that each cell responds best to a narrow range of sound frequencies. The outer hair cells are the sites of mechanical force generation in the cochlea which rapidly contract in response to membrane potential changes ~100 pN/mV. These otoacoustic emissions generate spontaneous sound from the ear [Fettiplace et al 2001].

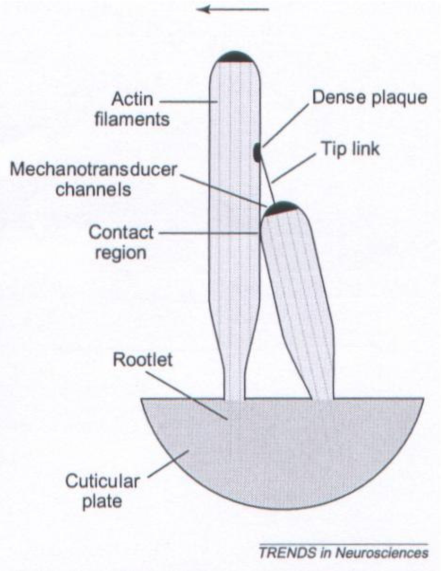


Fig 11-19 Intersterociliary connections – stereocilia is filled with actin filaments while myosin acts as a motor that climbs the acvtin filament to tension the tip link [from Fettiplace et al 2001]

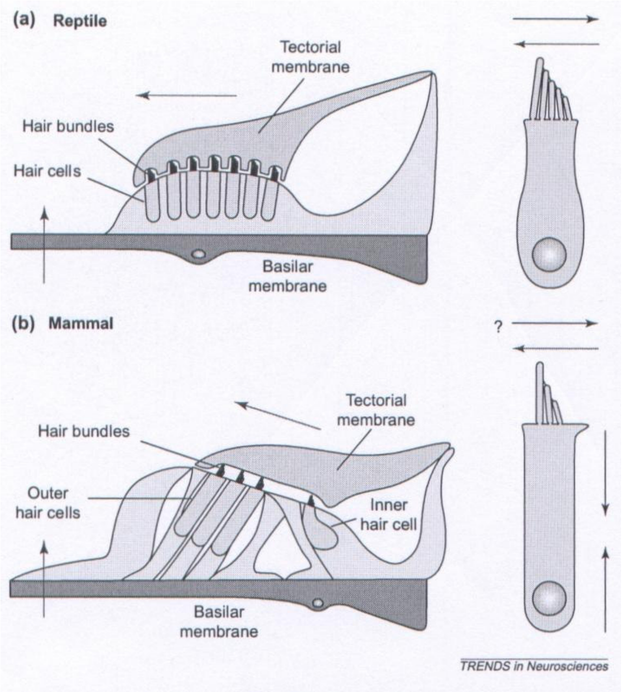
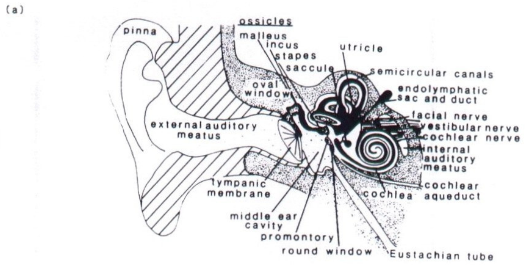
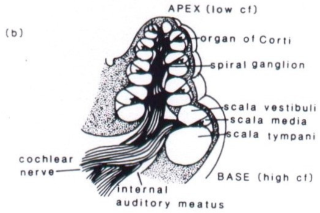
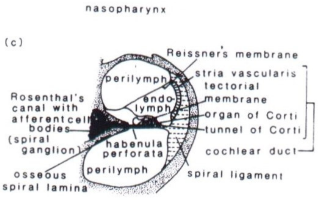


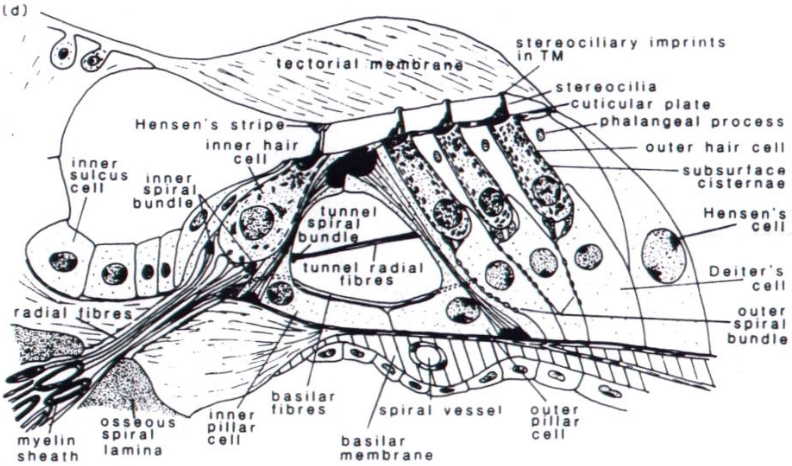
Fig 11-20 Twin functions of cochlear inner and outer hair cells – hair cell bundle bends towards taller edge and opens mechanotransduction cells and also mechanically amplify sound [from Fettiplace et al 2001]

The vibrations of cochlear membranes are amplified by energy from the hair cells to overcome damping of the perilymph fluids within the inner ear. The inner hair cells generate 20 myelinated afferent fibres (93% type I) forming divergent processes while around 10+ outer hair cells converge onto a single unmyelinated fibre (7% type II). The signals from the cochlea run in the auditory (VIIIth) nerve to the brainstem (superior olivary complex) where they bifurcate projecting cochleotopically to the cochlea nuclei. One pathway runs to the inferior colliculi while the other runs to the contralateral inferior colliculus. Both pathways run together to the medial geniculate bodies of the thalamus onto Layer IV and Layer II of the auditory cortex on the temporal lobe [Hackney 1987]. Non-language complex sounds which require complex spatiotemporal analysis are processed in the human planum temporale [Griffiths & Warren 2002]. This region represents the auditory association cortex which is required to segregate mixtures of acoustic sources from natural environments.


(a)
pinna
ossicles
malleus
incus
stapes
saccule
utricle
semicircular canals
oval window
endolymphatic sac and duct
facial nerve
vestibular nerve
cochlear nerve
internal auditory meatus
external auditory meatus
tympanic membrane
cochlear aqueduct
cochlea
middle ear cavity
promontory
round window
Eustachian tube


(b)
APEX (low cf)
organ of Corti
spiral ganglion
scala vestibuli
scala media
scala tympani
cochlear nerve
BASE (high cf)
internal auditory meatus


nasopharynx
(c)
Reissner's membrane
perilymph
stria vascularis
tectorial membrane
Rosenthal's canal with afferent cell bodies (spiral ganglion)
endolymph
organ of Corti
tunnel of Corti
habenula perforata
cochlear duct
osseous spiral lamina
perilymph
spiral ligament


(d)
tectorial membrane
stereociliary imprints in TM
stereocilia
cuticular plate
Hensen's stripe
phalangeal process
inner hair cell
outer hair cell
subsurface cisternae
inner sulcus cell
inner spiral bundle
tunnel spiral bundle
Hensen's cell
tunnel radial fibres
Deiter's cell
radial fibres
outer spiral bundle
basilar fibres
spiral vessel
outer pillar cell
inner pillar cell
osseous spiral lamina
myelin sheath
basilar membrane

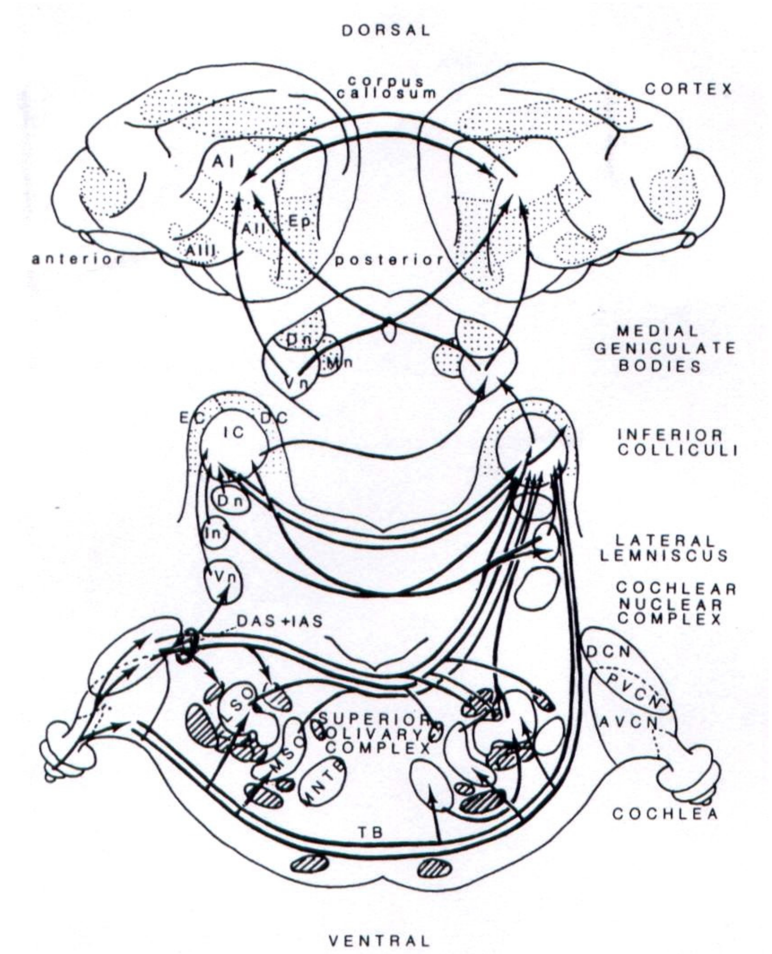


Fig 11-21 (a) section of outer, middle and inner ear of man; (b) guinea pig cochlea; (c) section of copchlear canal; (d) section through the organ of Corti (e) main ascending pathways from left cochlea [from Hackney 1987]

Motion detection enables prediction of future paths of moving objects. Nonmammalian species – birds, reptiles, amphibians – possess ears which respond to pressure gradient and thus can provide direct directionality information. Mammalian species however possess ears that respond to pressure. To acquire directionality, this requires sound shaping which only occurs at high frequency with wavelengths of around ear-sized – hence mammals have higher frequency hearing than non-mammals. Processing of acoustic motion motion cues is similar to that of visual motion based on interaural amplitude difference and interaural phase difference between the two ears detected by motion-direction sensitive neurons in the auditory cortex [Wagner et al 1997]. Interaural phase differences are dependent on the separation of the ears and are used by animals with large heads for low frequency detection (encoded within the medial superior olive). Frequency-specific amplitude differences at higher frequencies are stable and reliable cues extracted by comparing relative sound intensities between the two ears (encoded within the lateral superior olive). The barn owl is exceptional in that its ears are pressure gradient sensitive at low frequencies and large enough for high frequency pressure sensitivity [Cohen & Knudsen 1999]. Cues are processed in parallel, frequency-specific channels which is further processed in the midbrain and forebrain. Auditory space is represented in the brain by neurons with spatially restricted receptive fields forming an organised auditory map. In the midbrain, space is represented in maps but in the forebrain, space is represented in clusters of similarly tuned neurons.

The bat auditory cortex is suspected of performing Symlet wavepacket analysis from cross-correlating averaged potentials in response to auditory stimuli [Dear & Hart 1999]. Wavelet packets are used to decompose signals into smaller blocks particularly through translation and scaling changes. Symlet wavepackets have the further property of good time-frequency localisation useful for processing sonar signals. The moustached bat auditory cortex shows complex multiple frequency maps of combination-sensitive neurons for echolocation [Suga et al 1997]. Echolocation comprises a long constant frequency and short frequency-modulated components. The second harmonic of the continuous frequency component at 60 kHz is intense and provides for target velocity measurement with tuned neural filters. A large number of frequencies as generated by the frequency modulated component are required for target localisation and feature detection. The continuous frequency component is detected by coincidence detectors tuned to Doppler frequency shifts. The frequency modulated component is detected by coincidence detectors tuned to echo delay times. Velocity and range information is processed in separate partitions of the auditory cortex specialised for frequency and time domain processing respectively.

11.6. CHEMICAL SENSING

Chemical and biochemical detection offers particular utility for planetary exploration, traditionally undertaken by the alpha-proton X-ray spectrometer (APXS) and gas chromatograph-mass spectrometer for elemental and isotopic analysis respectively. Thus far, no spacecraft instrument has been deployed which can detect molecular moieties (though the Raman spectrometer offers some of this capability).

Taste is a chemical sense but is much less sensitive than smell – it can distinguish sweet (eg. sugar), sour (eg. citric acid), bitter (eg. quinine) and salty (eg. sodium chloride). However, there are suggestions of a fifth basic taste – unami, a savoury taste – which is sensitive to glutamates (eg. monosodium glutamate). The human tongue has 8000-10,000 taste buds, each of which has 50-75 chemical taste receptors. The University of Texas artificial tongue comprises an array of micromachined artificial taste buds etched onto a silicon sensor chip. Within each taste bud lies a small polyethylene glycol and polystyrene bead to which one of four different chemical sensors are attached. The beads act as taste receptors to solutions and change colour according to sweetness, sourness, saktiness or bitterness. The resultant colour spectrum is imaged by a camera and analysed by a neural network to define the chemical composition.

Smell is the most primitive sense and is a form of chemical sensing. Smell also is implicated in emotional memories. The olfactory bulb which processes smell is connected to the limbic system and this is connected to the hypothalamus. The nasal epthelium has between 10 to 100 million neurons, each sprouting 20-40 cilia receptors embedded in mucus. The tips of the cilia are coated with lipids and proteins which bind to odour molecules. When such a molecule binds to a receptor, the neuron fires an electrical signal to the brain. The average human can distinguish around 10,000 different smells. Each olfactory neuron expresses a single receptor gene and neurons with different receptors are scattered randomly around the nasal epithelium. There are 400-1000 different receptors in the human nasal epithelium. Receptors have a similar molecular structure except for a small unique binding region. Individual receptors are not specifically sensitive to a single odour but are sensitive to a range of different smells. Different smells are encoded by different combinations of receptors so that ~1000 receptors can detect ~10,000 different smells. On activation by binding of odour molecules to receptors, an ion gate is opened. Generally, birds lack olfactory senses but the turkey vulture *Cathartes aura* does possess a keen sense of smell. Insects and spiders often have good olfactory senses, hence their use of pheromones for communication. Spiders possess unusual olfactory hairs which are hollow and open at one end and supplied with nerve cells at the other. They are often clustered on the pedipalps and the first pair of legs. The human nose is a highly sensitive instrument of olfaction which may be emulated by arrays of electrochemical sensors connected to a PC and which may be trained to recognise gaseous chemicals, especially organic chemicals. The olfactory system receives input from the ciliated epithelial receptor cells of the nasal cavity. They convey messages to the mitral cells of the olfactory bulb. Mitral cell axons travel via the olfactory tract to the primary olfactory cortex in the medial temporal lobe. The sense of smell is interconnected with other parts of the limbic system. Olfaction is the only sense which does not pass through the thalamus due to its evolutionary ancience.

The olfactory system is unique in that it carries molecular information about odour molecules which generally have molecular weights of 26-300. It is essential for determining the identity of objects (food) and their state (rotting). Odour molecules bind to odour receptor proteins generating a signal in olfactory sensory neurons. Most natural objects emit specific combinations of 10s of different odour molecules which activate specific combinations of odour receptors in the nasal epithelium of mammals. The olfactory system detects mixtures of odourants which enter the nasal cavity and dissolve in the mucus overlying olfactory sensory receptors in the nasal epthelium. Odorant molecules bind to receptor proteins of 7 transmembrane G protein families generating ~1000 different types. This binding of odorant to receptors generates a series of biochemical events including adenylate cyclase and phospholipase messengers which open channels in the olfactory sensory neuron cell membranes. Depolarisation of the olfactory sensory neuron generates an action potential. Olfactory sensory neurons project to olfactory bulb glomeruli which converge the same receptor type inputs. Each odourant stimulates a large number of different types of receptors. The spatial and temporal pattern define the attributes of the odourant. Artificial noses are arrays of broadly specific sensors sensitive to vapours employing a pattern recognition system to identify the vapours [White et al 2002].

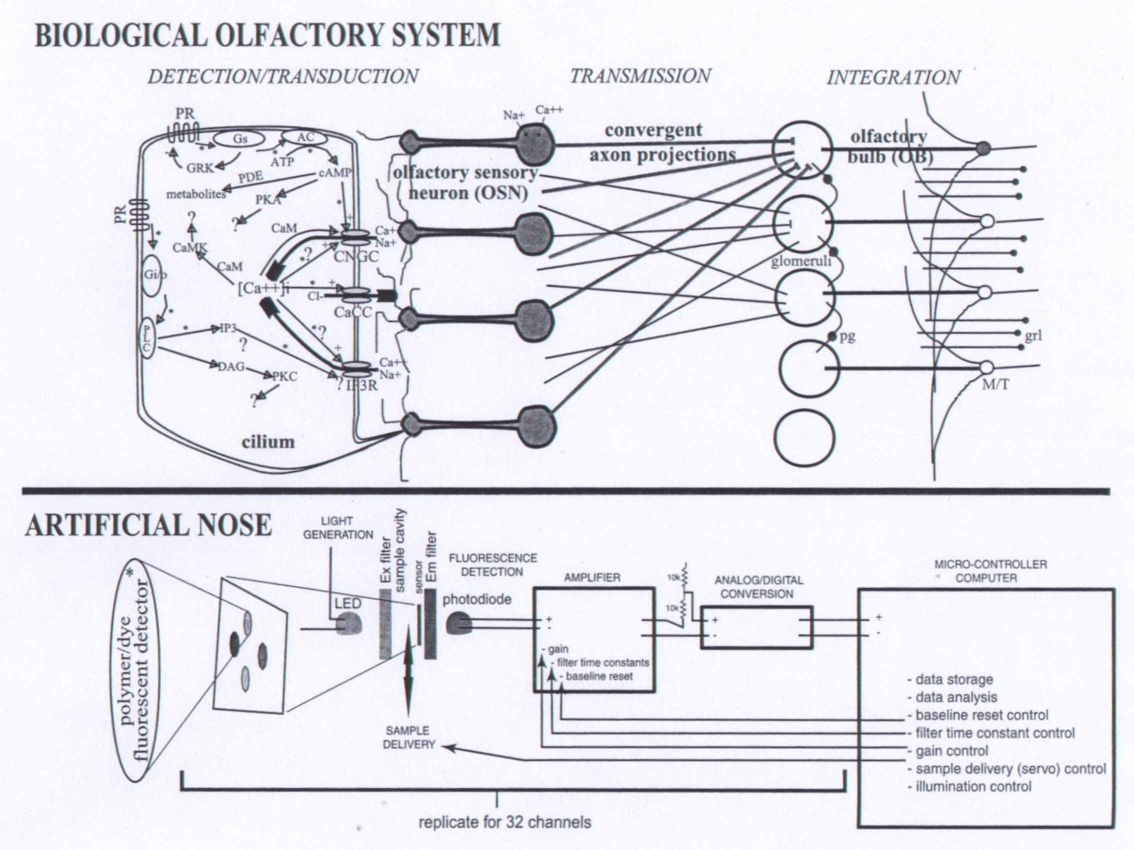


Fig 11-22 Comparison of biological and artificial olfactory systems [from White et al 2002]

Artificial noses can adopt an array of polymer fluorescent dyes such as Nile Red which alter their fluorescence on exposure to vapours. Sniffing can be emulated with a suction fan. The change in fluorescence by the dye illuminated by light emitting diodes are detected by photodiodes and amplified. Insect olfaction is fundamental to insect behaviour which is mediated through pheromones [Hansson 2002]. Their olfactory receptor neurons are broadly classified as specialist for insect pheromone detection and general for plant odour detection, but there are different degrees of specialisation for both types of receptor. Insect olfactory receptor neurons are housed within cuticular hairs into which odours pass through pores in the cuticle. Each hair is self-contained. This provides insects with the ability to discriminate between odour plumes. In insects, some 60,000 olfactory receptor neurons from the antenna converge on around 160 glomeruli of the antennal lobe comprising around 4000 local interneurons. Each local interneuron connects around 50-100 glomeruli. Glomerular projection neurons connect glomeruli with parts of the protocerebrum and mushroom bodies. In mammals, the olfactory system projects into the prefrontal cortex, entorhinal cortex, amygdala, hypothalamus and hippocampus which are associated with instrumental conditioning and memory formation [Slotnick 2001]. However, the organisation of the mammalian olfactory system is simple and does not rely through the thalamus and olfactory bulb projections terminate in the three-layered olfactory cortex. In insects, olfactory neuronal axons project into the antennal lobe containing 50-100 glomeruli, while in vertebrates, they project into the olfactory lobe containing ~10^3 glomeruli. Human odour discrimination can differentiate between some 400,000 odours at low concentrations ~10^{-7} but our recognition and identification of odorants is poor [Richardson & Zucco 1989]. There are reckoned to be six primary odour qualities – flowery, fruity, putrid, spicy, resinous and burned. The curious thing about classifying odour is that substances with similar molecular structures such as stereoisomers give odours that are quite different, eg. d-carvone and l-carvone. Conversely, chemically different substances can produce very similar odours. In mammals, there are two independent but similarly structured olfactory systems, the main olfactory system and the smaller accessory olfactory systems which detects conspecific pheromones and induces specific behaviours. The human piriform cortex is the primary region of the cortex devoted to olfactory processing, receiving projections from the olfactory bulb via the olfactory tract. It outputs to the forebrain including the entorhinal cortex onto the hippocampus, frontal cortex and thalamus. Thus, odours processed by the olfactory system have particularly emotive connotations and have a significant role in human memory. The piriform cortex is characterised by EEG oscillations (theta) at 7-10 Hz, each oscillation corresponding to a single sniff [Bower 1995]. The olfactory cortex acts as a kind of auto-associative network.

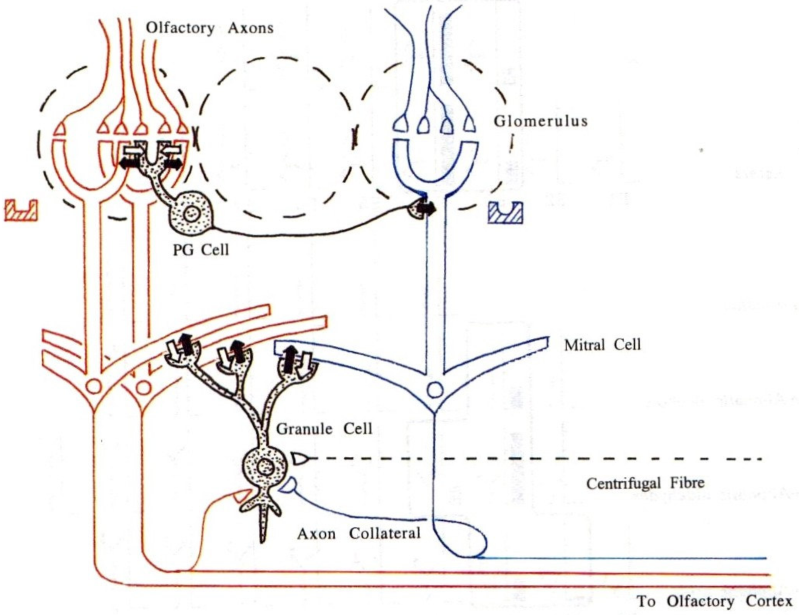


Fig 11-23 Basic local neuronal circuit in mammalian olfactory bulb [from Mori et al 1998]

Olfaction may be regarded as a form of chemical sensing which are commonly based on oscillator sensors. There are two types of oscillator sensor – surface acoustic wave and piezoelectric sensors. Quartz crystal microbalances are based on the piezoelectric effect whereby the application of an external electrical potential produces internal stresses [Chang et al 2000, O'Sullivan & Guilbault 1999]. An oscillating electric field applied across the crystal by an oscillation circuit induces an acoustic wave through the crystal perpendicular to the crystal surface. Deposition of a thin film on the crystal surface decreases the acoustic frequency in proportion to the mass of the film which if selective can be used to detect analytes of interest, ie. chemical vapour sensor, eg. polyimide films for humidity detection. The electrical oscillation frequency is designed to be close to the fundamental frequency of the crystal which depends on the crystal thickness, its chemical structure, its shape and its mass. The resonant frequency of the quartz crystal is given by:

$$f_0 = \frac{1}{2\pi\sqrt{(CL)}}$$

To detect analytes, the frequency change is related to the mass absorbed:

$$\Delta f = \frac{\Delta m f_0^2}{\sqrt{(\mu\rho)}A}$$ where A=surface area

ρ=density of quartz=2.648 g/cm^3
μ=crystal shear modulus=2.947 x 10^{11} dyn/cm^2 for quartz

If a liquid medium is used, the oscillation frequency depends on the solvent due to the shear wave in the fluid:

$\Delta f = f_0^{3/2}\sqrt{\left(\frac{\rho\eta}{\pi\mu\rho_q}\right)}$ where ρ=liquid density

η=liquid viscosity

Minimum mass changes that can be detected are ~1 ng/cm^2. Piezoelectric resonator oscillators offer lower oscillation frequencies (10 MHz) than SAW sensors (1 GHz) potentially offering 200 times the sensitivity of quartz microbalances. SAW devices are used for bandpass filtering and phase shift generation in rf electronics which have applications in phase-array systems. Quartz crystal oscillators provide timing references in both computer and communication systems. Surface acoustic wave sensors have been used for temperature, pressure, acceleration and stress measurement, gas detection, biopolymer characterisation, and humidity measurements. They are widely used in wireless radiofrequency applications as frequency control elements in rf oscillator circuits. Most surface acoustic wave devices are based on delay line oscillators [Galipeau et al 1997, Chang et al 2000].

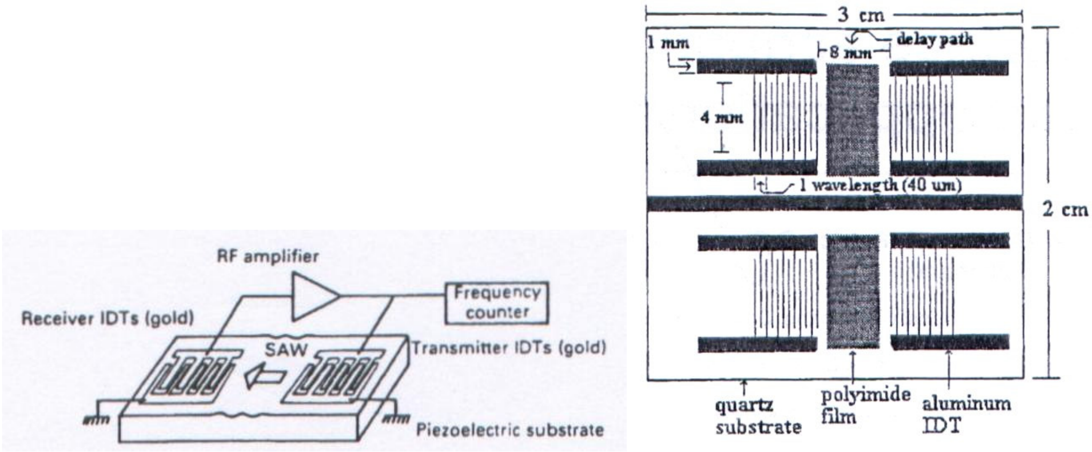


Fig 11-24 (a) Schematic of SAW sensor [from Chang et al 2000]; (b) Dual delay line SAW microsensor example [from Galipeau et al 1997]

The electrodes are metal interdigital transducers photolithographically etched onto the surface of the quartz crystal which are arrays of rf transmitters and receivers. An input rf voltage is applied across the transmitter interdigital transducers which induce deformations in the piezoelectric substrate which generate a Rayleigh surface wave confined to one acoustic wavelength of the surface. The wave travels across the gap to the receiver interdigital transducers which converts the mechanical wave back into an output rf voltage. Its velocity is given by: $v = \sqrt{\left(E/\rho\right)}$. The input and output is connected through an rf amplifier. If the oscillator gain exceeds unity, the circuit oscillates. The resonant frequency shift of a SAW oscillator and mass per unit area on the surface is given by:

$\Delta f = \frac{K f_0^2 \Delta m}{A}$

The widest use of SAW sensors is as microbalances.

Immobilisation of biomolecules is critical for biosensors as its sensitivity is dependent on concentration [Gilardi & Fantuzzi 2001]. There are several approaches.

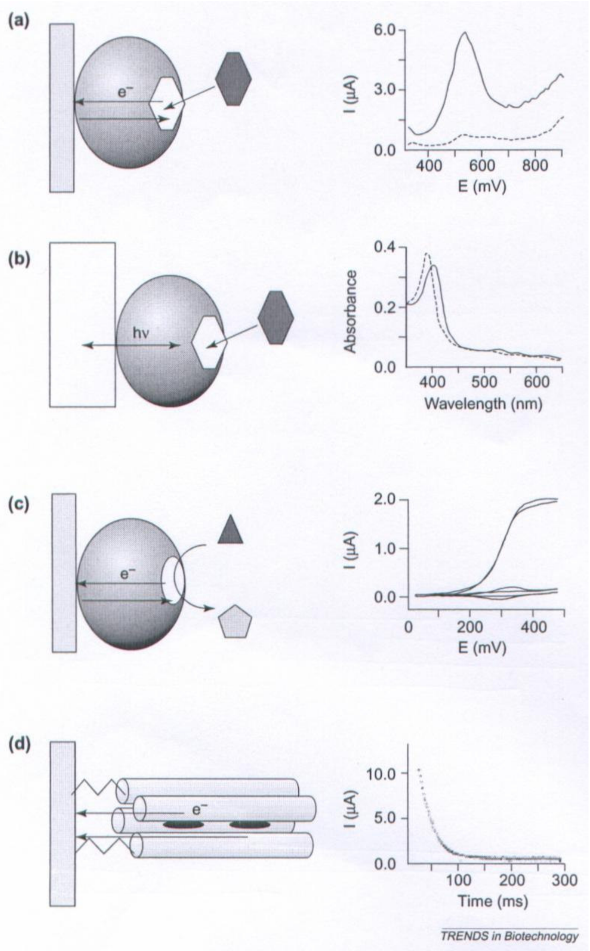


Fig 11-25 Redox proteins for nano-devices: (a) electrochemical device sensing the binding of ligand based on redox property changes (b) optical device sensing changes in redox centre optical properties; (c) detection of enzymatic activity by measurement of catalytic current; (d) proteins engineered with multi-redox centres immobilised on electrode surface [from Gilardi & Fantuzzi 2001]

Physical adsorption on metal oxide, carbon and silica oxide surfaces forms a randomly oriented layer but the protein may denature due to multiple interactions. Proteins may be trapped in either a polyelectrolyte or conducting polymer which results in a non-oriented multilayer film. Alkane-thiol or other thiol-terminated chains may be immobilised as a self-assembled monolayer on noble metal surfaces into which proteins may be immersed. Alternatively, the alkane-thiol or other thiol-terminatring chains may be covalently bonded to the noble metal surface as a self-assembled monolayer, the other end interacting with the protein. Direct site-specific attachment may be made with gold due to sulphur-gold bonds by genetically engineering a unique Cys residue on the surface of the protein (eg. azurin) or natural disulphide bond at the protein N-terminal with high control over orientation and packing. Cytochrome c has been immobilised on carboxyl groups of a gold-alkane-thiolate monolayer as a superoxide sensor which might have applicability to Mars surface exploration to test the hydrogen-peroxide theory. Bacteriorhodopsin may be oriented within a membrane or thin film deposited on a transparent (indium tin oxide) electrode which responds to changes in illumination with a photoelectric signal [Hong 1997]. Spike amplitude is proportional to differential intensity similar to an RC filter.

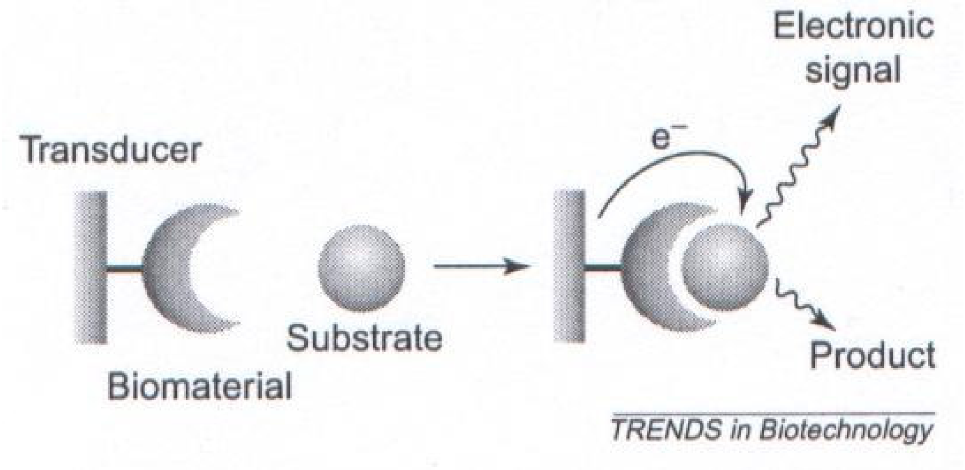


Fig 11-26 Electronic transduction of affinity interactions on transduction elements [from Willner & Willner 2001]

The detection of organic compounds may be considered to be the most important raison d'etre of astrobiology missions. Biosensors include a biological recognition component (eg. enzymes, receptors, immonoglobons, microbes, proteins or biological tissue), a physical transducer (which may be electrochemical, optical, thermal or most commonly mass-sensitive devices), an electrical amplifier and a data processing system [Sharma & Rogers 1994]. Biosensors incorporating enzymes have been developed to detect concentrations of carbohydrates, proteins, amino acids, and metabolites. Enzymes are governed by reaction kinetics such that reaction rate (mol/s), $R = {}^{R_{\max}}\!\big/_{(1+(K_m^+/[S])^n)}$ where [S]=reactant concentration, R_{max}=maximum reaction rate, K_m=Michaelis-Menten constant. At low concentrations such that [S]<<K_m, the reaction rate is proportional to the reactant concentration. Antibodies and receptors have advantages over enzymes including sensitivity to a wider range of compounds and better affinities giving detection ranges of 10^{-5} –10^{-10} M. Potentiometric measurements, commonly used for pH measurements, measure the potential due to the accumulation of charge which is related to analyte activity through the Nernst relation:

$E = E_0 \pm (RT/nF)\ln(a_i)$ where E_0 = standard potential
R = gas constant
F = Faraday constant
T = temperature
n = total number of charges on ion i

Ion-selective membranes make potentiometric device sensitive to specific ions. The ion-sensitive field effect transistor (ISFET) uses a gate voltage to modify the conductance between source and drain. The gate membrane is typically Si_3N_4 which is sensitive to protons. Optical fibre methods detect the fluorescence of a fluorophore excited by the electromagnetic wave, eg. fluorescence capillary and resonance mirror devices. Surface plasmon resonance uses a prism on which the external face has been coated with a thin metal film, typically gold. The surface coating matrix is covalently bonded to the metal surface, eg. carboxymethylated dextran mediated by carboiimide to immobilise antibodies. Incident light is reflected from the internal side of the metallised face which at a critical angle (dependent on refractive index of the prism) generates resonant oscillations in the metal film. The addition of analyte to the sensor surface increases the mass load detected by surface plasmon resonance. The key problem in biosensor design is to implement electronic coupling between the electronic component and the biomaterial [Willner & Willner 2001]. Electron transfer rate constant between an electron acceptor and a donor pair is given by:

$k = Ke^{-\beta(d-d_0)}e^{-(\Delta G_0+\lambda)^2/4RT\lambda}$ where d, d_0 = actual and van der Waal distances
ΔG_0 = Gibbs free energy
λ = reorganisation enery
β = electronic coupling constant

Redox sites in proteins insulate electroactive centres from electrical contact. However, the use of surface thin films on electronic components offers the means for achieving the integration of biomaterials on electronic devices. Biomaterials may be incorporation in organic/inorganic polymers and membranes, eg. functionalised thiolate monolayers on gold electrodes can form covalent bonds with biomaterials such as enzymes or antibodies. Water-soluble ferrocene derivatives and quinines can transport electrons from enzymatic active sites to electrodes. Monolayers comprised of pyrroloquinoline quinone-FAD/NAD have high electron transport rates. Integrated PQQ-NAD^+-LDH cross-linked arrays can be constructed on Al_2O_3 gate interface of a field effect transistor. Such systems may be exploited in biofuel cells which uses glucose as fuel and oxygen as oxidiser. Glucose oxidase on the pyrroloquinoline quinone-FAD monolayer electrode acts as the anode for oxidation of glucose. The cathode comprises a Cyt c-cytochrome oxidase electrode which biocatalyses four electron reduction of oxygen to water. This biofuel cell does not require a separating membrane. The maximum power output was 4μW at an external resistance of 0.9kΩ. Such biofuel cells might be used to power implanted devices. Neurotransmitter receptor proteins are good sensing candidates due to their high affinity and selectivity for specific ligands including amino acids and proteins but they are difficult to isolate. Immunosensors use binding protein antibodies as quartz crystal microbalance coatings for bioselectivity with high affinity and specificity. The chief difficulties are a lack of reproducibility in antibody immobilisation on the crystal surface and viscous drag in liquid phases. Immobilisation methods include non-covalent adsorption, covalent bonding and membrane entrapment. Electrochemical conducting polymers incorporating enzymes such as glucose oxidase polymerised in polypyrrole have ready control of thickness at the electrode surface but enzymatic reaction involving H_2O_2 degrade polymer conductivity. Protein A (a protein which binds specifically to the Fc portion of the IgG immunoglobin) is the most widely used pre-coating for antibody immobilisation for detecting chemicals, viruses and bacteria. Langmuir-Blodgett films have been used for detecting lipids. Self-assembled monolayers of thiols and sulphides have been used for immobilising antibodies to the gold surface of piezoelectric crystals which form antibody-thiol complexes. A maleimide-monolayer functionalised gold electrode reacted with anti-immunoglobin G(IgG)$F(ab)_2$ antibody can detect the anti-*Chlamidia trachomatis* lipopolysaccharide antibody. The major limitation of immunosensor devices is that the high affinity antigen-antibody complexes are not separable after sensing. Reversible immunosensors may be implemented using a reversible photoisomerisable antigen monolayer interface (eg. dinitrospiropyran monolayer which binds to dinitrophenyl antibody) on a quartz crystal whereby the monolayer acts as the antigen for the antibody. Once detected, the monolayer is photionised to a conformation that releases the antibody. DNA oligonucleotides can also be immobilised on quartz crystals using complementary DNA oligonucleotides to detect the target DNA on hybridisation. Detection of DNA and RNA have primarily been enabled by optical sensing arrays. Thiophosphate thymine tagged oligonucletide monolayer on a gold electrode reacts with the analyte DNA complementary to a segment of the analyte. A secondary binding of avidin-horseradish-peroxide stimulates oxidation of 4-chloronaphthol by water to an insoluble product providing the means to detect DNA. Whole cells may be used in biosensors which provide a lare supply of enzymes, access to natural enzymatic pathways, and enhanced enzyme stability [Wijesuriya & Rechnitz 1993]. Self-assembled bilayer lipid membranes (BLM) resembling the self-assembly and self-healing of hydrophobic cell membrane lipid bilayers may be used in biosensors and solar energy conversion [Ottova et al 1997]. There are two ways to form BLMs – a modified Langmuir-Blodgett method uses two partitions in each of which a lipid monolayer is spread in a volatile solvent such as n-hexaner which are then combined; the conventional method uses a dynamic agar gel on a freshly cleaved Teflon-coated solid conducting substrate capable of accommodating modifiers such as polypeptides, proteins, etc. A BLM equivalent circuit is given by RC parallel circuit: $I = I_C + I_R = \frac{V}{R_m} + C_m A$ where A=area of BLM. Bacterial membrane channel forming proteins - porines – form anion-selective pores which may be incorporated in a liposome and fused with BLMs. They can incorporate a variety of compounds such as enzymes, antibodies, receptors, redox species, etc to detect antigens, hormones, electron donors/acceptors, etc. The incorporation of dipyridyl tetrathiafulvalene (DP-TTF) into BLMs exhibits sensitivity to H_2O_2. pH sensors sensitive to hydrogen ions can be created by incorporation of quinonoid compounds (chloranils). The incorporation of C-60 greatly strengthen the stability of BLMs and imparts photosensitive functions. Given the importance of electron transfer across biomembranes in biological energy generation and storage, BLMs can be doped with photosynthetic pigments and photon-absorbing molecules to generate significant photovoltages and photocurrents which may be exploited to create electrochemical cells. An excellent review of the manufacturing techniques for electrochemical biosensors is given by Zhang et al (2000). The problem with the use of biological molecules is their limited temperature tolerance.

Thin films of different metalloporphyrins have been used as sensing materials to develop optical sensors to detect different volatile organic compounds which on absorption of the analyte change their absorption properties [Natale et al 2000].

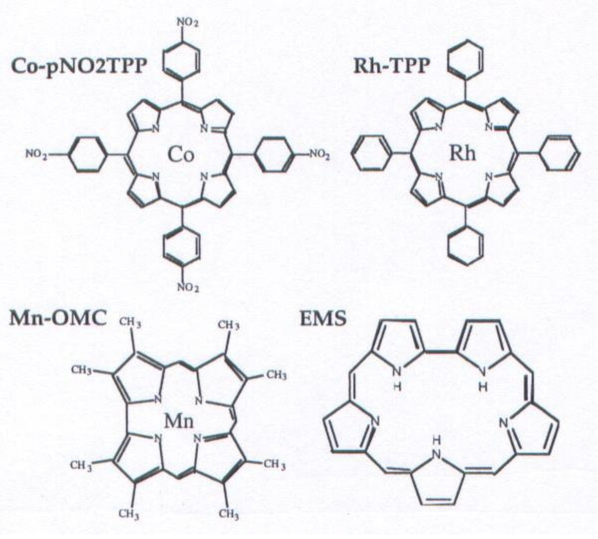


Fig 11-27 Structure of chemicals used as sensitive layers [from Natale et al 2000]

Porphyrins have absorption and luminescent characteristics due to the electronic transitions within the π-bonds of the aromatic structure. Metalloporphyrins have ligands at the axial positions which influence the electronic structure of the molecule. In the solid state, π-π interactions generate broad absorption spectra which on absorption of organic material modify the spectra. Thin films of metalloporphyrins have broad selectivity making them suitable for electronic noses. Optical UV-visible transmission spectrophotometer may be used to detect the spectra (typically in the blue region) on exposure and adsorption of compounds like alcohols, ketones, aldehydes and amines due to changes in π-π interactions. Sapphyrin is best at detecting amines and organic acids.

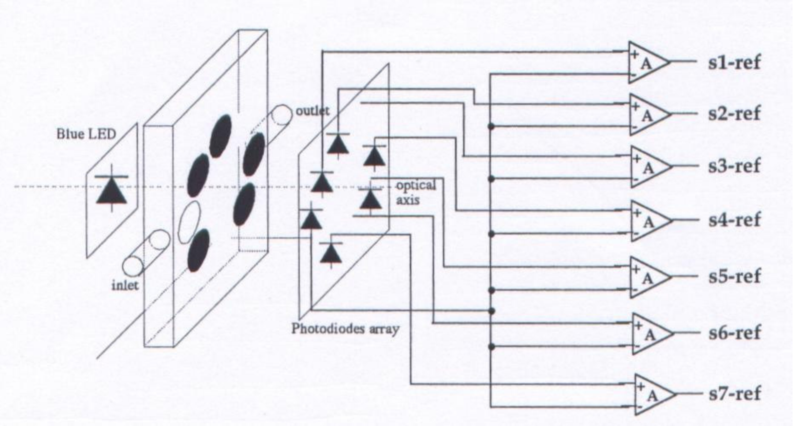


Fig 11-28 Opto-electronic nose with one reference pathway for comparison with photodetector outputs [from Natale et al 2000]

Many electronic noses operate on the principle of resistance changes within conducting chemisensitive films [Partridge et al 2000]. Typically, conducting polymers or non-conducting polymers loaded with conductive filler are used. The inert insulting polymer (eg. PVC) is mixed with an electrically conducting powder (carbon black) between two electrodes. The polymer absorbs gas when exposed, expanding the matrix and increasing the electrical resistance of the film. Chemical sensors made from different conductivity polymers embedded with carbon black particles provide an array of large bandwidth. When the polymers absorb molecules from odourous chemicals they swell due to hydrophobicity, eg. benzene is hydrophobic. Plastics comprise of tangled fibres which swell when organic molecules are absorbed between the strands. Carbon black may be scattered among the strands and if the polymer is non-conducting, (ie. any plastic can be used), carbon black provides the only pathway for electric current to flow. If the polymer swells, the electrical pathway is disrupted reducing the conductivity of the material. Different plastics swell to different degrees depending on their chemical affinities. Even doping concentration will affect the behaviour of the material, eg. 10-20% carbon black will exhibit different behaviours. The organic matter impregnating the plastic will alter their conductivity and so alter the magnitude of the electric current passing through them. Different polymers respond differently, so each chemical species may yield a unique electrical fingerprint. A greater variety of sensors yields a greater diversity of discrimination among a wide variety of chemicals. A 5-10 sensor head is reckoned to provide good results. Commercially available plastics are suitable, eg. polystyrene (hydrophobic), polyvinyl alcohol (hydrophilic). Artificial olfaction may use artificial neural networks to learn patterns of responses associated with different chemicals. This requires training to recognise any given species. Repeated exposure provides good discrimination ability. Nasal cavity design may be crucial in determining airflow patterns over the epithelial layer of the nose, eg. dogs have more intricate folding of the nasal cavity than humans. The nasal epithelium cavity is studded with ~10M sensory cells (each with $\sim 10^3$ different chemical receptors) for decoding in the olfactory bulb. Surface acoustic wave (SAW) sensors may be utilised to pass acoustic waves along a thin wafer of material. Any change in the mass of the wafer causes a change in the velocity of the waves which may be measured accurately. Covering the wafer with an imprinted polymer means that the mass will change when target molecules are present. A sheath of optical fibres with ends coated with plastics mixed with fluorescent Nile Red dye can act as sensors to odourous organic chemicals. Light is shone down fibres to the tips to make the dye flouresce characteristically at a different wavelength according to the swelling of the polymer. Part of this light may be reflected up the fibre to be measured by CCD camera into a digital electrical signal for analysis by the ANN. The flourescence offers additional variables for diversity - intensity, wavelength and flourescence duration. These devices can distinguish between structures differing by only a single carbon atom. Commercial noses take around 1-2 minutes to fingerprint smell as they need a steady reading at controlled temperatures. A variety of methods of analysis may potentially cope with this problem, eg. Kalman filtering. Potentially, such architectures could be reduced in size to chip level with sensors and ANN integrated onto a single silicon chip. For example, several 1mm wide wells may be etched onto a 1cm wide silicon wafer connected to a PC. Each well has deposited in it a different type of sensor material. The zNose uses sound waves to detect the chemical composition of a vapour and is a form of fast gas chromatography. The odour mixed with He is passed through a heated column. Different molecules travel at different speeds depending on their molecular weight. They arrive at the end of the column at different times and the odour molecules impinge on a quartz crystal. The quartz crystal is effectively a SAW device which shifts its frequency of vibration when a molecule impinges on it in proportion to the molecular mass of the odour molecules giving an indication of its concentration.

The potential for small, low-mass, low power and relatively inexpensive artificial noses is large, including interplanetary probes for sampling planetary atmospheres for trace amounts of complex organic compounds.

11.7. MAGNETIC FIELD SENSING

Many vertebrates can detect the Earth's magnetic field for navigation (compass reference, field intensity and field inclination) which are based on two main transduction mechanisms – biogenic magnetite and magnetic field modulated chemical reactions [Lohmann & Johnsen 2000]. Electromagnetic induction has been suggested for elasmobranch fish (sharks, skate and rays) whereby the ampulae of Lorenzini function as conducting bars which induce a voltage drop in seawater detected by electrorecptors – this requires a conducting medium and cannot operate in air. Magnetic field sensitive chemical reactions operate through influencing nuclear and electron spins and orbits – this generates a precession effect in an ambient magnetic field. Such magnetoreceptors are expected to function as photoreceptors which, by inducing photo-excitation, enhances the precession effect, eg. retina. Magnetite (Fe_3O_4) minerals exist in magnetotactic bacteria and in honeybees, birds, fish and others. They may function in a variety of ways, either directly on ion channels or via secondary pressure/torque receptors. Only magnetite methods can give magnetic polarity, inclination and field intensity variation information. No demonstrable primary magnetoreceptors have been identified in vertebrates as they may be small, embedded and dispersed in large volumes of tissue.

11.8. SENSOR FUSION

Sensors can provide multiple information sources which operate in parallel. For complex environments, it is desirable to simultaneously integrate such sensory data from diverse multiple sources. Multisensor data fusion improves the overall performance of interpretation and classification by providing a more reliable and robust estimation of the environment than each sensor considered alone. Sensor suites offer redundant information with different fidelities or offer complementary information of different modalities. It decreases feature ambiguity, uncertainty due to noise and reduces search spaces during matching at later processing stages. The commonest fusion proposals have been the fusion of stereoscopic vision sensors, the fusion of vision information with range finder information, and the fusion of visual and tactile data. Although multisensor fusion is believed to occur in the human brain, ventriloquism seems to indicate that visual information dominates auditory information in the fusion process [Luo & Kay 1989]. Furthermore, space adaptation syndrome (space sickness) also suggests that sensory fusion processes are not complete with vision dominating over vestibular data, the mismatch being the cause of the nausea characteristic of the condition. Fusion essentially involves the integration of different sensory modalities into a single representational format such as a world model.

Animals have to integrate different sensory modalities. The fruit fly *Drosophila melangoster* must fuse three sensory modalities in order to locate food – olfaction, vision and mechanoreception [Dickinson M et al 2000]. Each has different characteristics: fly vision have excellent temporal resolution due to their high flicker rate ~300 Hz (compared with human temporal resolution of 20-30 Hz) which affords good optic flow capability but poor spatial resolution; olfaction is the main distance sensor whereby attractive odours are detected by chemosensory receptors within the antennal glomeruli; mechanoreceptors are required on the antennae to determine wind direction. Halteres are mechanoreceptors which act as gyroscopic sensors for roll, pitch and yaw for stable flight. Initially, fly trajectory is mediated by olfaction in two ways: its horizontal motion is mediated directly by olfaction which alters firing thresholds to direct it to the source while its vertical motion is mediated by olfaction indirectly by integration with visual data. Tethered flies turn away from visual expansion. The outputs from motion detector cells across neighbouring regions are used to estimate vertical and horizontal expansion. This generates a series of saccade generating signals proportional to the expansion front/rear/left/right. This is opposite to the behaviour of bees which orient themselves away from moving visual patterns. This behaviour of flies is believed to result from overriding rotation signals from the more rapidly processed halters whereby in the absence of visual and odour stimuli flies fly with haltere control only.

A common central environment for the integration of sensor data may be provided by a distributed blackboard architecture to provide high level sensor fusion with each sensor module passing messages to the blackboard [Harmon et al 1986]. The blackboard provides centralised control of multiple specialist knowledge sources. Shafer et al (1986) called their blackboard model of sensor fusion a whiteboard since it represented a topological map of the scene using potential fields and the modules were separate expert systems dedicated to mobile robotic behaviour for their NAVLAB mobile robot: CAPTAIN, NAVIGATOR, PILOT and PERCEPTION expert subsystems. Sensor fusion was implemented by integrating through the whiteboard map with other processes. The simplest fusion strategy involves raw sensor measurements of the same property obtained from multiple sensors being combined (direct fusion) [Hackett & Shah 1990]. Before fusion can occur consistency between diverse data sources must be determined to check that they represent the same physical entity. The Mahalanabis distance which should be small for the same representative object can determine this:

$d = \frac{1}{2}(x_i - x_j)^T C_k^{-1}(x_i - x_j)$ where x_k=sensor output

C_k=variance-covariance matrix

For two sensors with scalar outputs this reduces to:

$d = \frac{(x_1 - x_2)^2}{\sqrt{\sigma_1^2 + \sigma_2^2}}$ where σ_i=standard deviation of sensor measurement.

The simplest way to fuse data is to use Bayes maximum likelihood ratio to model the sensor uncertainty. Bayes theorem assigns probability on the basis of evidence.

Bayes rule is given by:

$p(\theta|X)=\frac{p(X|\theta)p(\theta)}{p(X)}$ where X=sensor output
θ=object property
$p(X|\theta)$=probability of output being X given property θ
$p(\theta|X)$=probability of property being θ given output X

$p(X|\theta)$ is determined from the sensor model. The best estimate of object property θ using k sensor readings is given by the likelihood estimate with θ chosen so that it is maximised:

$$p(\sum_{i=1}^{k} X_i|\theta)=\sum_{i=1}^{k} p(X_i|\theta).$$

As logarithms are easier to manipulate:

$$L(\theta)=\sum_{i=1}^{k}\log[p(X_i|\theta)] \text{ where } p(X_i\,|\theta)=\frac{1}{\sqrt{(2\pi)^n C_i}}e^{-\frac{1}{2}(X_i-\theta)^T C_i^{-1}(X_i-\theta)}$$

Hence, $L(\theta)=\sum_{i=1}^{k}(-\frac{1}{2}\log[(2\pi)^n C_i]-\frac{1}{2}(X_i-\theta)^T C_i^{-1}(X_i-\theta))$

The best estimate $\hat{\theta}$ is found by differentiating $L(\theta)$ with respect to θ and equating to zero:

$$\hat{\theta}=\frac{\sum_{i=1}^{k} C_i^{-1}X_i}{\sum_{i=1}^{k} C_i^{-1}}$$

For two sensors with scalar outputs: $\hat{\theta}=\frac{(\sigma_2^2)x_1+(\sigma_1^2)x_2}{\sigma_1^2+\sigma_2^2}$

More complex fusion strategies involve such techniques as the weighted least squares fit and the recursive Kalman filter. The extended Kalman filter is the commonest approach to data fusion from separate data sources. Indeed, the first Kalman filter ever flown was aboard the Apollo Lunar Module primary computer to process rendezvous data for rendezvous with the Command Service Module in lunar orbit. The Kalman filter uses a dynamic model for the time evolution of the system and a model of the sensor measurement system to find the most accurate estimation of the system's state using a linear estimator based on the present and past measurements [Raol & Sinha 1985, Lefferts et al 1982]. It is a recursive predictive updating method that estimates the parameters of a model with new measurements while incorporating the effects of noise (assumed to be Gaussian white noise). The error between parameter estimates and measurements of those parameters is used to update the parameter estimates through a gain matrix. Its chief characteristic is its use of the statistics of the sensor measurements (measurement error covariance). Measurement is usually modelled as a Gaussian probability distribution requiring an estimate of the mean and the variance-covariance matrix. Given the possibility of implementing Kalman filters through neural networks, this may represent a reasonably plausible biological analogue. The recursive Kalman filter estimation algorithm can be used to merge data from multiple images into a composite by assuming Gaussian errors [Porill 1988]. For a normal distribution the probability distribution function is described by its mean and covariance. For a measurement, the expected error $<x>=\bar{x}$ and the covariant measurement matrix is given by:

$$C=\text{cov}(x)=<(x-\bar{x})(x-\bar{x})^T>=<xx^T>-\bar{x}\bar{x}^T$$

This assumes a normal distribution function of the form:

$$p(x)=\frac{1}{(2\pi)^2\det S}e^{-\frac{1}{2}(x-\bar{x})^T C^{-1}(x-\bar{x})}$$

A composite object measurement is characterised by $\overline{X} =< x_1 \ldots x_n >^T$ and C=diag(c1...cn) corresponding to each primitive descriptor. It is necessary to find the optimal update of $\hat{X}$ and $\hat{C}$ given a measurement of Z related to X by Z=HX+u where H=plant matrix and u= measurement error with zero mean and known covariance. If no previous measurements have been made $\hat{X} = 0$ and $\hat{C} = I$. The optimal update rules are given by:

$\hat{C}' = \hat{C} - \frac{(\hat{C}h)(\hat{C}h)^T}{h^T \hat{C} h}$ and $\hat{X}' = \hat{X} - K(Z + h^T \hat{X})$ where $K = \frac{\hat{C}h}{h^T \hat{C} h}$

h=sensor dynamics matrix

12. Spacecraft Reliability

12.1. INTRODUCTION

The use of redundancy (both hardware and functional) is the commonest approach to spacecraft reliability. A system with m units will function as long as k of m units function correctly. The probability of k of m units functioning correctly is given by:

$$P(k,m,p(t)) = \binom{m}{k} p(t)^k (1-p(t))^{m-k}$$ where p(t)=probability of single unit functionality

$$= e^{-\lambda t}$$

λ=failure rate
=219 /10^9 h for MIL-HDBK-217 64k DRAM

Hence, reliability, $$R_{system} = \prod_{i=k}^{m} p(t)^i (1-p(t))^{m-i} = \prod_{i=k}^{m} \binom{m}{i} e^{-i\lambda t}(1-e^{-\lambda t})^{m-i}$$

The exponential model of failure does not account for infant mortality which has been a significant problem in the latest generation of communication satellites but does model post-infant mortality reasonably well.

Reliability and maintainability are related concepts through system operational availability (a measure of system performance). For any space project, it is desirable to increase operational availability within the budgeted cost restraints. In traditional engineering, high availability requires a mixed approach since [Ellery 2000]:
Availability, A=(MTBF/(MTBF+MTTR+MTFS)
where MTBF=mean time between failures and reflects reliability
MTTR=mean time to repair and reflects maintainability
MTFS=mean time for supply and reflects logistic capability

$$MTBF = \int_0^\infty R(t).dt = \int_0^\infty e^{-\lambda t}.dt = \tfrac{1}{\lambda}$$ for a component

$$MTBF = \int_0^\infty \prod_{i=k}^{m} \binom{m}{i} e^{-i\lambda t}(1-e^{-\lambda t})^{m-i} = \tfrac{1}{\lambda}\prod_{i=k}^{m}\tfrac{1}{i}$$ for a system

The traditional approach in spacecraft engineering is to impart high availability by maximising reliability while ignoring maintenance for reasons of inaccessibility of spacecraft. Reliability is typically achieved through the use of high reliability components (with the costly implication of a history of space qualification) and the use of redundant systems (with the costly implication of either added mass to be launched into orbit and/or reduced front-end payload which provides the commercial return). The current approach to spacecraft availability yields high mass and cost to space missions, particularly for modern extended life commercial platforms such as geostationary comsats which have been developed for 15 year lifetimes. It is apparent that on-orbit servicing (OOS) reduces MTTR by increasing maintainability and MTFS by providing logistics capacity. The biological variant to such maintenance is self-maintenance and self-repair.

12.2. BIOLOGICAL RELIABILITY

Self-repair is a much desired capability for spacecraft to reduce reliance on reliability through redundancy. The capacity for regeneration of specialised tissue depends on the ability of its cells to undergo mitosis. Bone is one such self-repairing organ which is subject to continuous destruction and generation of bone material. The human skeleton is 80% cortical bone and 20% trabecular bone. Cortical bone is predominant in long bones and on the exterior of all bones – it is solid and hard. Trabecular bone is spongey and occurs in the inner regions of bones to allow the passage of marrow and red blood cells. Bone is continuously formed and resorbed by metabolic activity controlled by bone cells. This provides the basis for the repair of tissue from insult. In tissues such as skin, muscle, cartilage, tendon and epithelial surfaces, active regeneration occurs by growth inwards from the edges of a wound. Endocrine and liver glands, although they cease to multiply in adults, have the potential for mitosis initiated by the appropriate stimuli. The central nervous system has no regenerative capability after birth. Peripheral nerve cells cannot multiply but their axons may regenerate as long as they enter the appropriate Schwann cells peripherally.

Biological wound repair is ubiquitous in biology. The edges of the gap within a wound fills with blood clot (formed by platelets) and serum in which the fibrin (derived from the coagulant factor fibrinogen) forms a matrix in which fibroblasts and angioblasts grow from the wound edge. Eventually, granulation tissue is formed between the wound edges and the fibroblasts contract into collagen (scar tissue) by the action of platelets on fibrin. Granulation tissue is comprised of fibroblasts and angioblasts infiltrated inflammatory cells. Inflammation is the reaction of tissue to injury. Acute inflammation involves initial dilation of blood vessels due to the vrelease of hisamine, 5-hydroxytryptamine and other vasodilators. Serum, white blood cells and antibodies pass through the capillaries into the tissue. Chronic inflammation involves the proliferation of fibroblasts and fibrocytes, macrophages and plasma cells.

12.3. RECONFIGURABLE HARDWARE

Self-diagnosis and self-healing are much desired capabilities within autonomous spacecraft. Reconfigurable hardware such as two-dimensional array-based FPGAs (such as the Xilinx Virtex series) offer an approach to biologically inspired fault tolerance with the ability to adapt hardware configuration in real-time to solve changing requirements of a system and variations in its environment. There are two types of fault tolerance [Hollingworth et al 2000]. In adapting fault tolerance occurs when the evolutionary system designs the hardware around faults as they are encountered. Evolved fault tolerance occurs when fault tolerance is afforded by evolutionary strategies. In adapting fault tolerance, genetic algorithms/programs behave as optimising processes where the evolutionary algorithm is halted once a given fitness is attained, ie. continuous real-time adaptation to environmental changes. Diagnosis and reconfiguration of processor cells may be distributed among all cells in the processor array – this eliminates single point failure mode using a central processor [Ortega & Tyrell 1998, 1999]. Every cell in the FPGA array stores its own configuration register and also those of its neighbours. Each cell selects its configuration register according to its position in the array defines by its coordinates relative to its neighbours. An address generator assigns a set of coordinates to each cell depending on its south and west neighbours. The logic block is controlled by a configuration register selected by the cell's coordinates. The configuration register defines the cell's functionality and its routing. Every cell stores stores the configuration registers of all the cells in its column.

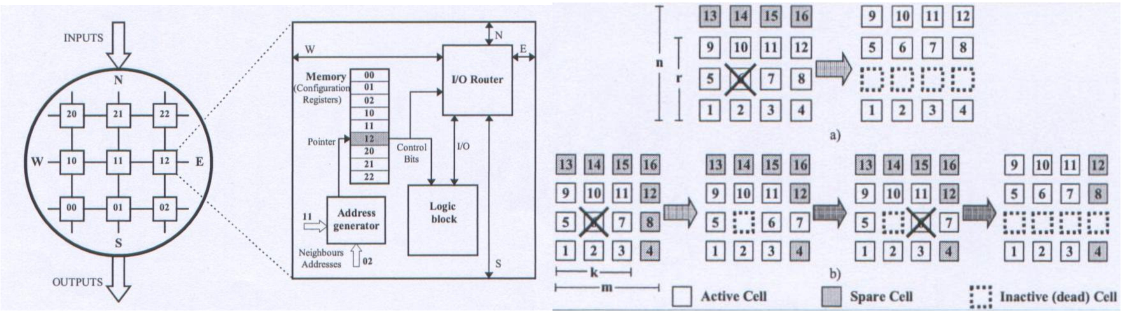


Fig 12-1 (a) Basic components of an embryonic system; (b) Fault tolerance by (i) row elimination and (ii) cell elimination [from Ortega & Tyrell 1998]

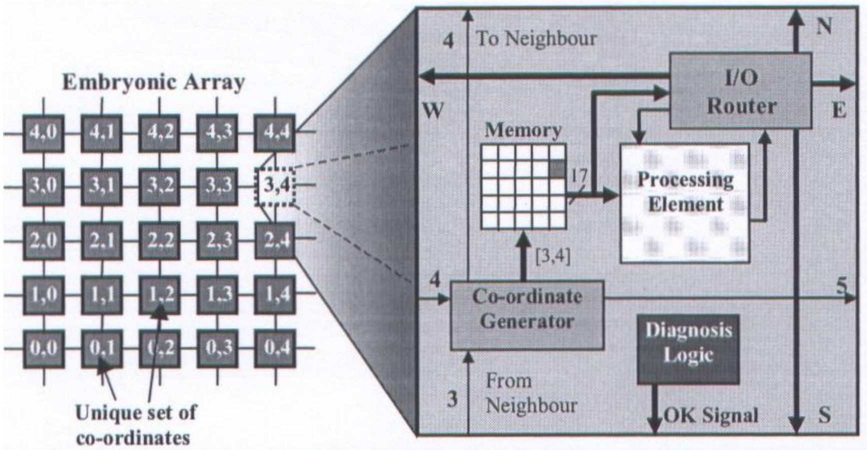


Fig 12-2 Generic architecture of an embryonic cell [from Ortega & Tyrell 2000]

This emulates cellular differentiation in which different instructions of DNA during development are interpreted according to the cell’s position within the embryo (embryology+electronics=embryonics). The fertilised egg divides my mitosis with identical genetic material inherited by all cells. Cells differentiate into different tissue according to instructions stored in the genome depending on the position of the cell within the embryo. Each cell of the array performs continuous self-checking (built-in self-test) and if failure is detected, the cell issues a status signal that disables it and invokes a reconfiguration mechanism which causes each surviving neighbouring cell to re-compute its position and store a new configuration register. In row elimination, the failure of one cell invokes elimination of the corresponding row. Although row elimination removes sound cells, the algorithm is simple and, for large arrays, the loss of cells increases linearly while the array area increases quadratically. In cell elimination, one spare cell per row is included plus one spare row. Fault invokes replacement by spare cells until all spare cells are used when row elimination is invoked. This has a higher reliability with high efficiency but cell complexity increases. The use of redundant nodes is exponential to the square root of the size of the array while cross-strapping provides the same dependeability where redundancy is logirthmic to array size. The MUXTREE architecture implements each cell as a multiplexer with configuration register memory implemented as a look-up table [Ortega & Tyrell 2000, Hollingworth et al 2000].

12.4. MULTI-AGENT ARCHITECTURES

One approach to reliability is redundancy through the use of multi-agent units. Multiple satellite constellations offer high performance, low unit cost, higher fault tolerance, reconfigurability and upgradability. Each may be treated as an individual autonomous agent and the constellation comprises a distributed processing system [Campbell & Schetter 2002]. They typically communicate through message passing.

Distributed multi-agent systems effectively decomposes constraint satisfaction problems into several not entirely independent subproblems which are subcontracted to different problem-solving agents each of which have their own goals but which effectively implement parallel computation. Multiagent systems are also tolerant of failures and their modularity makes them highly scalable. Multiagent systems are characterised by granularity, heterogeneity, architecture, communication protocol [Stone & Veloso 2000]. Agent-based methods are based on the notion of autonomy, sociality, reactivity, pro-activeness, mobility, veracity, benevolence and rationality. Agents are intentional systems with beliefs, desires, etc which are attributed on the basis of observed behaviour. Beliefs are difficult to implement in first order logic as intentions are referentially opaque and are not truth functional, eg. the truth value of "Alex believes p" does not depend on the truth of p [Wooldridge & Jennings 1995]. There are seven properties required of a theory of intention [Cohen & Levesque 1990]:

- (i) intentions pose problems for agents which require solution
- (ii) intentions filter other intentions to ensure no conflict
- (iii) agents track success of their intentions
- (iv) agents believe their intentions are possible
- (v) agents do not believe they will not bring about their intentions
- (vi) agents believe that they will bring about their intentions
- (vii) agents may not intend all the expected side effects of their intentions

An agent has a persistent goal of p I and only if

- (i) it has a goal that p eventually becomes true and believes that p is not currently true
- (ii) before it drops goal p, one of the following conditions must hold:
  - (a) agent believes p has been satisfied
  - (b) agent believes p will never be satisfied

Intention is an intention to act by performing action a if it has a persistent goal. Speech acts define communicative utterances as actions similar to physical actions [Searle 1969, Cohen & Perrault 1979]. They are performed by the speaker with the specific intention of causing a desired change in the state of the world by altering the mental state of the listener. Representative speech acts are informing and directive speech acts are requesting.

Social insects – ants, termites, bees and wasps - exploit redundancy through multiple agents. There are almost 9000 species of ant which live in large numbers within a colony. The workers are sterile females each armed with a stinger. All colonial insects have a caste system where different individuals are specialised for different tasks. Pheronomes are used for communication in such insects. Termites resemble ants in living in caste-based colonies. Both ants and termites have co-existed for 100 million years but they are rivals for nest sites. Ants are generally the primary aggressors due to their periodic colony migrations. Termites use their soldier caste and chemical warfare for defense. The pinnacle of multi-agent co-operation is the construction of a termite nest with a multitude of termites exhibiting purposeful behaviour as a single entity. This activity emerges from a multitude of disorderly movements as termites randomly transport and drop small quantities of earth mixed with hormones. They move randomly until a small initial but sufficiently critical quantity of earth is accumulated at a number of points. The termites are then attracted over longer distances by the stronger concentration of hormones at these points and the probability of more earth and hormones being dropped there is reinforced. The application to construction activities such as digging, levelling or piling of regolith by microrovers is obvious. To enable the microrovers to swarm as teams they would require infrared beacons mounted onto their structures. Each rover activates behaviours that move it toward the greatest concentration of beacons but at an offset distance from all other rovers. To operate as a coordinated pack one microrover disables its swarm behaviour and activates its leader behaviour while the other microrovers activate their swarm behaviours. In this way they can act as a colony which behaves as if under purposeful control. Each rover is then a semi-autonomous unit in that a community is created by the communication of messages.

Complex systems in biology arise from the interaction of a large number of simpler components characterised by global behaviour indiscernible from the component behaviours – artificial life research attempts to model such emergent phenomena using cellular automata [Wolfram 1986]. Artificial life is based on the notion of simulated ecological systems which explore how simple interactions between agents generates higher level phenomena. Agents interact through mating, trading and conflict. Each agent has a set of rules which determine its interaction with other agents. These rules are encoded within the agent's genome. An agent reproduces itself when it accumulates sufficient resources to make a copy of its genome. Such simulations generate arms races between two competing species through more complex offensive and defensive strategies.
Cellular automata are characterised by only local dynamics with no long-range connections for transmitting information. Robustness of such systems to perturbations is provided through dissipation such that only certain properties survive over time, many initial conditions dissipating away through viscous damping – such systems are irreversible. The dynamics may be characterised as following basins of attraction for each fixed point, each basin bounded by a watershed defining a "category" to which the system may evolve. Some basins may be fractal (chaotic), eg. Julia set: $x \to x^2 + c$. Cellular automata are dissipative, irreversible modes of computation which evolve to attractors. Class 1 and 2 cellular automata evolve to attractors which are fixed or limit cycles whereby small changes in initial states are damped out. Types 3 and 4 cellular automata however exhibit chaotic behaviours whereby small changes in initial states possess divergent behaviours. Cellular automata are regarded as universal models of computation.

A variation on the multi-agent approach is metamorphic re-configurable robots constructed from a set of autonomous connectable units. Each unit must comprise of a battery power source, a micro-controller, two motors, four pairs of infreared transmitters/receivers for communication and/or proximity sensing, and four docking connectors. Each module has two degrees of freedom – pitch and yaw. Modules can be connected together by their docking connectors. At the back is a female connection port while the front, left and right faces have male connectors. The hormone is a meassaging system which has three main characteristics:

(i) it is a global broadcast with no specified destination
(ii) it has a finite lifetime
(iii) it triggers different effects at different receivers

Salemi et al (2000) have implemented a gait-specifying hormone which may be emitted by one module and detected by another module – however, the one-way broadcast approach is not conducive to synchronisation. Hormone propagation is the process by which a module sends a message to all its links to other modules. On receipt of a hormone, a module relasys it to all its neighbours. Hormones can wait at a site until certain triggering events occur before being passed onto other modules. They can be used as tokens to synchronise events between modules. Parallel actions begin simultaneously while serial actions start consecutively. A module infers that all other modules start their actions when it receives hormones from its neighbours through all its active

links. There are two types of hormone – action-specifying hormones and synchronisation hormones:
ASH (task, action, lifetime, maximum time)
SH (task, hormone list, lifetime, maximum time)

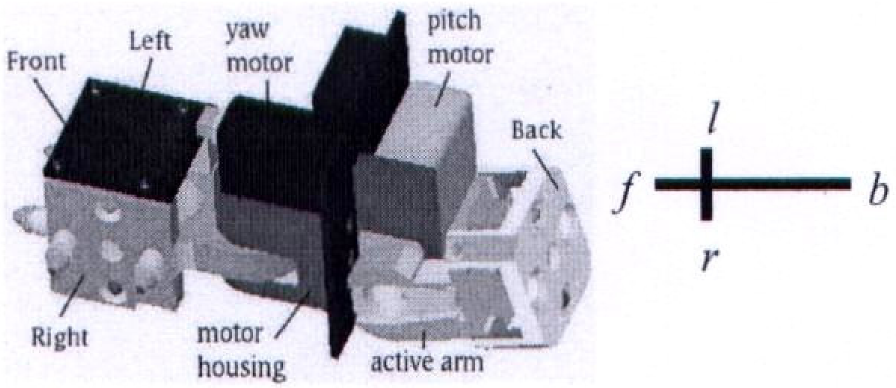


Fig 12-3 Autonomous module of self-reconfigurable robot [from Salemi et al 2000]

For parallel synchronisation, in performing a task, a module selects an action and propagates an action-specifying hormone through all its active links to its neighbouring modules. On receipt of action-specifying hormones, modules send out synchronisation hormones to asll its neighbours. The hormone-based message passing system requires only $O(t^2n)$ messages compared with standard message passing protocols which requires $O(n^2)$ messages. For serial synchronisation, synchronisation hormone is sent only once the action has been performed. The CELL algorithm has the following form:

```
WHEN (task) received DO
  Select gait with parallel synchronisation;
  If (synchronisation of selected gait is parallel)
     Select Action (selected Gait)
     While (task specification hormone is active)
          Propoagate (selected Action)
          ParallelSynchronisation()
          Execute (selected Action)
          Select Next Action (selected Action, selected Gait)
  If (synchronisation off selected gait is serial)
     Select Action (selected Gait)
     While (task specification hormone is active)
          Execute (selected Action)
          Propagate (selected Action)
          Select Next Action (selected Action, selected Gait)
```

Self-organisation occurs in social insects which exhibit complex collective behaviours which emerge from simple individual behaviours. Self-organisation is a set of dynamical interactions between elementary units from which global structures emerge. The elementary interactions are specified by local rules. Self-organisation requires a number of properties [Bonabeau et al 1997]:

(i) positive feedback (amplification) due to recruitment and reinforcement
(ii) negative feedback to stabilise collective patterns due to saturation or competition
(iii) random fluctuations due to errors, etc

(iv) multiple interactions between a mimimum density of individuals

Characteristic signatures of self-organisation include:

(i) creation of spatiotemporal structures within a homogeneous medium
(ii) coexistence of multiple stable states to which the system may evolve
(iii) existence of bifurcations when some parameters are varied

The termite Macrotermes uses soil pellets impregnated with pheromones to build pillars. The non-coordinated phase is characterised by random deposition of pellets until one deposit reaches a critical size. The coordination phase occurs when an initial deposit of pellets stimulates workers to accumulate more material through positive feedback due to the increased attractivity of deposited pheromones. This autocatalytic effect requires a minimum density of workers. The general mechanism is that initially termites are distributed evenly between pheronome sources but due to random fluctuations, one source becomes slightly favoured. This subsequently becomes amplified through recruitment of other ants thereby reinforcing the signal. Ant (Lepthorax) building is based on bulldozing by 500 worker ants and a single queen whereby each ant carrying soil granules pushes the granules into other granules already in the nest [Franks et al 1992]. Other examples of self-organisation include coordinate large prey-carrying in ants, thermoregulation in bee hives, larval sorting by ants, etc (the last two are based on the use of temperature and humidity gradients). Flocking is characteristic of many animals and occurs through independent individual behaviour to navigate according to its local perception and social environment. Biological flocks occur without central control – such behaviour has been replicated through “boids” (simulating birds, fish or herds) which are subject to three simple locals rules within a 3x3 force field [Reynolds 1987]:

(i) match direction and speed of neighbours (velocity matching)
(ii) head for average position (flock centring)
(iii) do not collide with neighbours (collision avoidance)

Flocking emerged automatically through weighted averaging as long as errors in direction do not stir the flock into dispersal. Mataric (1995,1996) has extended the range of basic behaviors for group coordination to include: avoidance, safe-wandering, following (complement to avoid-everything-else), aggregation (inverse of dispersion), dispersion for group avoidance (extension of safe-wandering), and homing navigation to a goal location (local pursuit).

Safe-wandering:

```
Avoid-kin:
Whenever an agent is within d_avoid:
    If the nearest agent is on left, turn right
    Otherwise turn left
Avoid –Everything-Else:
Whenever an obstacle is within d_avoid:
    If an obstacle is on right only, turn left
    If an obstacle is on left only, turn right
    After 3 consecutive identical turns, backup and turn
    If an obstacle is on both sides, stop and wait
    If an obstacle persists on both sides, turn randomly and backup.
Move-Around:
    Otherwise move forward by d_forward, turn randomly
```

```
Follow:
Whenever an agent is within d_follow
    If an agent is on right only, turn right
    If an agent is on left only, turn left
```

Disperse:
Whenever one or more agents are within d_disperse, move away from centroid_disperse

Aggregation:
Whenever nearest agent is outside d_aggregate, turn toward local centroid_aggregate, go
Otherwise, stop

Home:
Whenever at home, stop
Otherwise turn toward home, go

Temporal and concurrent activation of multiple basis behaviours produce higher-level collective behaviours, eg. flocking, foraging:

Flock:
Sum outputs from safe-wander, disperse, aggregate, and home

Forage:
Whenever crowded, disperse
Whenever at home
    If have pellet, drop pellet
    Otherwise disperse
Whenever sense-pellet
    If not have-pellet, pickup-pellet
Whenever behind-kin, follow

Interference between individuals within a social group can be minimised using social rules which must be applied as credit from the environment may be delayed or non-existent [Mataric 1994, 1997]. Interference acts to block goal-driven behaviour due to resource competition or goal competition. The dominance hierarchy is ubiquitous in which animals minimise conflicts (though changes to dominance involve conflict). Such social behaviours include: yielding, proceeding, communicating and listening. These social rules involved proceeding when near and to near a stopped agent, yielding when near a moving agent, listening when reeiving a message and broadcasting a message when food is found. Social learning involves learning how to perform (through imitation), when to perform through social facilitation. Three types of reinforcement learning are necessary: individual perception of progress, observation of conspecific behaviour, and reinforcement from conspecifics.

The Prisoner's Dilemma is a simple two person game that is used to model social interactions. Each player has the choice of cooperating or defecting. If both players cooperate, they gain 3 points. If one player defects and the other cooperates, the defecting player is awarded 5 points while the cooperating player receives zero points. If both players defect, they get 1 point each. For any player, the best single strategy is to defect – the prospect is for 1 point or 5 points which is better than 0 or 3 points in cooperating. However, this strategy of always defecting gives a lower total payoff than if they both cooperated in sequential games. The tit-for-tat strategy cooperates on the first move and reciprocates the other player's response thereafter. In dynamic environments however, genetic algorithms have evolved strategies that begin with defection initially but then begin to reciprocate.

Self-organisation for formation flying and self-assembly may be implemented using two simple behaviours – approach and avoid. Approach may be implemented through equilibrium shaping (based on potential fields) whereby the equilibrium points of a dynamic structure are shaped within a velocity field. The avoid behaviour is implemented as an inverse repulsion law at close proximity between objects.

One biomimetic argument for exploiting multiagent systems is that this is generally reckoned to have been the route to intelligent species – primate intelligence evolved as a result of social interactions. Most such multiagent systems are based on predator/prey systems – typically with one prey and one or four predators - which are nonetheless "toy" domains [Stone & Veloso 2000]. The goal of the predator is to capture or trap the prey within a grid-like world while the prey attempts to evade capture. The most successful strategies are the "ignorance is bliss" without multi-agent communication whereby different agents exploit different resources as they have only partial local information. Non-communicating agents can affect each other indirectly through affecting the environment and so sensory inputs to another agent (active stigmergy) or through altering the environment so that the effects of another agent change (passive stigmergy). The degree of heterogeneity between agents may be defined through social entropy. Competitive learning generates an arms race. The utility of cooperative versus competition is commonly modelled by the prisoner's dilemma. The dilemma is solved in iterative versions whereby self-interest is served by cooperation. Without communication, it is necessary for agents to learn by observing each other. Communication however opens up new possibilities of distributed strategies which are far more effective than independent local strategies, particularly when communicating goal information. Speech acts model this aspect of communication. Social conventions provide the means cooperative coordination.

12.4.1. Imitation Learning

Reinforcement learning requires representation of states and actions with a reward function. Learning proceeds by attempting actions and based on received rewards, updating the evaluation function to maximise reward. Learning by imitation offers a promising approach to autonomous social humanoid robots for efficient motor learning, sensorimotor association, and coordination of motion primitives [Schaal 1999]. Imitiation requires a sophisticated multi-representational interaction between perception, memory and motor control. It is however the fastest form of learning behaviours than more traditional conditioning methods. Imitation refers to copying an observed feature of body movement by another. There must be a specific causal relation between observation of the body movement on the demonstrator and execution of the same movement by the observer. Imitation may be regarded as a non-verbal test for the attribution of intention. The ability to imitate has the following properties:

(i) imitated behaviour is new to the imitator
(ii) same task strategy as that of the demonstrator is employed
(iii) same task goal is accomplished

Imitation is exhibited by higher intelligences – neonatal humans, chimpanzees and birds - due to the requirement for the detection and analysis of movements which use intention, attention and memory at high levels of representation. This is required in order to translate visual information about the body movements of others into matching motor output. Neurons within the superior temporal sulcus respond to movements of specific body parts and faces. The left inferior frontal gyrus – specifically areas 44 and 45 - appears to be specialised for imitation such that its neurons recognise body movement through activation of premotor and motor areas [Heyes 2001]. This subsumes Broca's area and is the human homologue of the monkey area F5 - neurons in the monkey area F5 are specific to goal execution related to movement sequences, eg. reaching, grasping, etc. Many are active during part or whole of the motor act, indicating motor schemas. Indeed, some neurons – mirror neurons – are active during both observation and execution of specific behaviours – these are mental simulations based on predictive forward models. The perceived actions of the teacher are mapped onto a set of existing primitives during assimilation. The most relevant primitives are adjusted by learning to improve the performance during the accommodation phase. Task-level imitation requires prior knowledge of how a task level command can be converted into motor commands. A reverse model is required by which inputs from the model are compared to the observer's motor output. In addition, a forward model is required to predict the output given the activation of a set of motor actions. The development of imitation is experience-dependent comprising a set of bi-directional between sensory and motor representations of motor acts. These associations are formed by co-activation from correlated experience of observation and execution. Billard & Mataric (2000) have developed a motor skill imitation simulation between two humanoid robots.

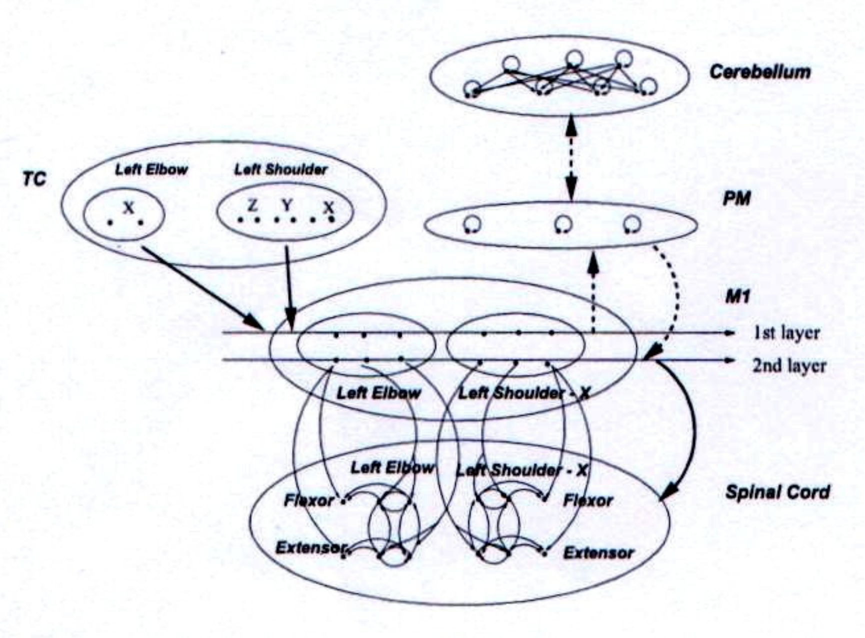


Fig 12-4 Structure of neural modules for humanoid motor skill acquisition [from Billard & Mataric 2000]

The model included spinal cord, primary and pre-motor cortex, cerebellum and temporal cortex connectionist modules. The spinal circuits implement central pattern generators. The temporal cortex module performed recognition of movement direction of teachers' limbs relative to an intrinsic coordinate frame (input Cartesian position coordinate of each limb joint). Motor control was by spinal cord module and primary motor cortex module, both of which output directly to motor neurons. Motor cortex can also innervate spinal cord directly. Premotor cortex coordinates and plans complex sequences of movement. Learning of new motor sequences is performed in the premotor cortex and the cerebellum modules. Primary motor cortex contains a motor map of the body which activate distinct extensor-flexor muscle pairs. One extensor-flexor pair controlled one degree of freedom joint. The primary motor cortex receives input from the visual system and the premotor cortex. Premotor cortex learns excitation patterns of the primary motor cortex in order to recognise limb movements. The cerebellum learns timing of motor sequences so the cerebellar module learns temporal combinations of movements encoded in the premotor cortex. Each muscle was modelled as a spring-damper system of the form:

$$m\tfrac{d\ddot{\theta}}{dt} = (k_e e - k_f f)\theta + (k_{pf} - k_{pe})\dot{\theta} - mg\sin\theta$$

where e,f=motor neuron amplitudes for extensor/flexor muscles
k_e,k_f=extensor/flexor muscle spring constants=0.3
k_{pf},k_{pe}=extensor/flexor muscle damping constants=30

Motor skill sequences learned included repetitive arm and leg movements, oscillatory shoulder and elbow movements, and precision hand movements for reaching and grasping.

Communication is defined as a signal which provides the basis for manipulating the environment through other agents. Indeed, sociality is reckoned to be the primary evolutionary force for emergence of human intelligence – the agent learns through interaction with consecific agents. Furthermore, sociality is essential for objectification of self and the implementation of intention. The subject of experience requires an indexical reference to the present situation. Given that language involves the interaction with other agents and the environment, theory of games may be used to model generative language. Meaning of symbols are generally fixed by mutual understanding – this requires a shared context [Levin 1995]. The evolution of language is grounded in the sensorimotor level of behaviour. Language and meaning may originate from physically grounded social groups [Steels 1998]. Language is premised on the concepts of space, time, objecthood, events, relations, etc. Language syntax and semantics co-evolve with shared ontologies despite the fact that agents cannot inspect the internal states of other agents. The basic scenario assumes a shared environmental context, each agent perceiving their current environment, and then categorising the different objects within that environment [Steels 1997]. There are four types of relevant adaptive language game (between a hearer and a speaker) which co-evolve to generate syntax and semantics [Steels 1998] – imitation game is used to replicate common sounds, discrimination game is used to distinctions between objects, naming game to form a lexicon, and assimilation game to generate syntax. Both syntax and semantics emerge through experience of word-meaning associations compatible with situation. The speaker chooses a distinctive feature set and encodes this into spoken symbols. The hearer decodes the utterance by matching words in his lexicon. The hearer extracts the feature set and compares it with his expectations. If no lexical entry exists, one is created associated with the feature sets. Learning language by imitation provided the basis of teaching a basic vocabulary concerning objects in a robot's envirionment [Billard & Dautehahn 1998, 1999]. In this approach communication is grounded through situatedness and embodiment within its physical environment. The imitative approach (mutual following) creates a common perceptual context for the learner and teacher. Multiple associations of words between temporal sensory sequences (object-signal associations) was performed by a Dynamically (fully connected) Recurrent Associative Memory (DRAMA) which provided short-term memory of external events, learning of temporal sequences and retrieval of learned associations. Honeybees communicate through a waggle dance language which encodes different flower types and locations.

12.5. IMMUNOLOGICAL FAULT TOLERANCE

Immune system is ideal for modelling using genetic algorithms as the mapping from genotype to phenotype is simple. The immune system is capable of recognising almost any ~ 10^{16} foreign cell or molecule that invades the body. It can distinguish between the body's own cells from foreign cells. The immune system further is a distributed system without a central controller. The genetic algorithm can be used to model somatic mutation which evolves antibodies to match specific antigens. Antibodies and antigens are modelled as binary strings to represent B and T cell receptors o antibodies and epitopes on antigens. Recognition occurs when complementary strings generate molecular binding. This can be used to generate V-region (variable) multigene libraries. Immune system analogues are closely related to classifier systems [Farmer et al ?]. The universal principle that underlies the immune system function is recognition of self from non-self. During development, B cells that produce self-antibodies are destroyed. Human immunity is provided by a dual system comprising soluble antibodies and special immune cells. Specific immunity is initiated by non-specific immune cells – phagocytic cells. Phagocytosis in an innate immunity system that comprises the first line of defense against a broad range of organisms. Phagocytic cells engulf and ingest foreign material which is digested and chemical components processed for use by the specific immune system. However, this process fails when there are large numbers of micribes. Acquired immunity exists to provide specific protection which is based on the fact that microbes carry different kinds of proteins (antigens) on their surfaces. Antibodies are produced by Be cells – each B cell produces a specific antibody that can bind to a limited type of antigen. The antibodies are expressed on the surface of the cell as receptors. When the antibody receptors of a B cell recognise an antigen, that B cell is stimulated to reproduce and thus proliferate (clonal selection). A few antigens, such as bacterial cell wall polysaccharides can stimulate B cells directly and specifically. Such B cells produce low levels of their IgM. The epitope is a small region of the antigen of a few amino acids with a distinct configuration that is recognised by a distinct antibody or T cell receptor. This highly specific ligand/receptor interaction of antigens and antibodies underlies the principle of molecular recognition and provides the basis for recognition of non-self from self. Acquired immunity involves the production of B and T lymphocytes and antibodies. An antibody is a complex protein composed of four chains held together by covalent (eg. disulphide) and electrostatic bonds. The genetic material for one antibody moleculer is stored in five separate component gene libraries, from which random selection from each library generates the antibody. There are 5 different types of antibodies, the most common being IgG (secondary response). These different antibody classes have different heavy chains – IgG (dominant in secondary response), IgM (dominant ~75% in primary response), IgA (important in mucus secretions), IgE (anti-worm immunity), and IgD (B cell receptor co-expressed with IgM). There are two heavy (~50,000 MW each) and two light chains (~25,000 MW each) – the variable region comprises one heavy and one light chain and the constant region comprises the other heavy and light chains. This generates a Y-shaped structure such that each antibody has two equivalent binding sites for its specific epitope located at the ends of the short arms of the Y. The constant region lies at the base of the Y and part of the arms. The constant region have mostly the same amino acid sequence for each of the five types of antibody. The two constant regions of the heavy chain together form the Fc region which attaches to macrophages. The variable region has variable amino acid sequences to generate unique antibodies – this is where the epitope resides. The variable region lies at the ends of the arms of the Y. One B-cell expresses antibodies of a single specificity. Different epitopes on antigens are recognised by distinct lymphocytes with different specifities. Antibodies are membrane proteins on the surface on B-lymphocytes which firstly, bind to antigen molecules on the surface of pathogens and secondly, recruit other molecules to destroy the bound pathogen. Each function resides on a separate structural region of the antibody. The antigen-binding region lies in the variable region, and the recruitment region lies in the constant region. B lymphocytes ingest and present antigen in order to proliferate and differentiate. Most of the antibodies produced after the first exposure are IgM (primary response). B cell proliferation activates somatic hypermutation. Somatic hypermutation affects genes that encode for the antibody molecule (especially the variable region which encodes the epitope). Daughter cells of a stimulated B cell have a wide variation in their binding ability to the antigen. Competition between these cells yields B cells with antibodies with higher affinities for the antigens. There are three types of T cell – killer T cells, helper T cells and suppressor T cells which have similar specificity as B lymphocytes. Antigen-presenting cells (APCs) include macrophages, dendritic cells and B cells. All ingest macromolecules and microbes by phagocytosis. Macrophages in particular are long-lived phagocytes found in many tissues – they contain lysomoes full of digestive enzymes to break down foreign molecules. Dendritic cells are found in lymphoid tissue. Only if the antigen is presented by membrane proteins MHC (major histocompatibility complex) II can it be recognised by helper T cells. The APC-MHC II-peptide complex is recognised by a T cell only if that T cell possesses a complementary receptor CD4 to help it bind to MHC II of the APC. When the T cell and APC interact, they secrete cytokines (eg. interferon-g). The helper T cells with CD4 and Th-1 antigens cause unique B cells to proliferate, mature and secrete antibodies – the helper T cells react only with B lymphocytes that recognises the same antigen that activated the T cell causing the B cells to proliferate by clonal selection. It is macrophage activation that is inhibited in AIDS due to the lack of T helper cells. B cells also ingest antigens but are specific to the antigen. Killer T cells recognise foreign antigens on the surface of host cells (eg. in viral infection and cancer cells) which proceed to attack and destroy infected host cells. Killer T cells secrete lymphokines which cause inflammation. Suppressor T cells monitor and adjust antibody levels in the body and suppress helper, killer T cells and B cells at the end of infection. Lymphocytes, on maturation (in bone marrow for B lymphocytes and in the thymus for T lymphocytes), acquire distinct surface receptors which provide them with antigen specificity. Genetic recombination involves the cutting and splicing of genes to produce a large number of genes that encode antibodies. The maturation process involves recombination of genes coding for the variable regions. Some gene segments are randomly deleted, so that each developing B or T cell acquires its own unique combination of genes, eg. a human host can possess up to $\sim 10^8$ different specifities (yet the complete genetic code comprises $\sim 10^5$ genes). Immunological memory is a specific function of specialised cells formed during adaptive immune response – at any one time, the antibody library size is ~100. The memory cells are small lymphocytes and such memory-type responses have been traced to the earliest metazoa – sponges – which possess cytotoxic reactions following sensitisation and specific reactivity.

The antibody-antigen bond strength may be modelled as the difference between the free energies of the complex and the reagent molecules. Furthermore, each molecule has a Gaussian deviation from the average energy. The fitness is determined by the strength of the bond between the antibody and the pathogen [Oprea & Forrest 1999]. In particular, patterns of bit strings may be used to represent molecular shapes and their ability to form bonds with other molecules. Antigens and antibodies may be represented by bit strings of the same length. The evolution of antibodies for recognising and binding to antigens is based on matching of their complementary shapes. Binding affinity between antibody and antigen is determined by the number of complementary matches of the respective binary strings. This match score defines its fitness. For a population of N antibodies at each generation, there is a fixed set of U antigens to which each generation is exposed to K antigens randomly chosen. The fitness of the individual antibody is the average of of the match scores for the different antigens divided by the antigen string length. The greater the match between the antibody and antigen, the stronger the molecular binding between them. The larger the size of the antigen universe U, the greater the degradation in the performance of the genetic algorithm in evolving antibodies. However, the larger the exposure to antigens K, the faster and higher the evolved fitness. However, the most rapid and highest fitness results from increasing the antibody population N [Perelson et al 1996]. If the Hamming distance between two similar antibodies is small, they will recognise many of the same antigens. Such overlapping coverage of antigens provides redundancy but reduces antigen coverage. However, optimal coverage requires maximum antigen coverage balanced with coverage redundancy. This has been demonstrated through fitness of an immune system correlating with the Hamming separation of the gene segment libraries [Hightower et al 1993]. The Baldwin effect suggests that acquired characteristics can be incorporated into the genome of future generations without Lamarckian inheritance. Individuals can learn or acquire useful characteristics during their lifetimes enhancing their survival and offspring. Succeeding generations have a higher probably of acquiring the same characteristics. The

Baldwin effect has been modelled in the immune system indicating that learning leads to increased evolutionary progress. Learning rewards individual antibodies that are closer to the threshold binding energy [Hightower et al 1996].

The physical contact between T cells and their targets occurs at a specialised structure, the immunological synapse for T cell adhesion. This forms a specialised cell-cell junction with a central core of T cell receptor and protein kinase Cθ, and an outer ring-like structure of integrin LFA-1 and talin membrane cytoskeleton proteins. The synapse core constitutes a protected space for signalling and effector functions such as CD2. The outer ring forms a gasket of adhesion molecules.

13. Human Spaceflight

13.1. INTRODUCTION

We consider only briefly issues related to life support systems. Regenerative life support systems involve the regeneration of the basic resources of oxygen, water and food. They involve physical or chemical altering of resources with waste management by using non-useful waste products to recover useful resources, ie. through recycling. Their major disadvantage is that they require increased power and thermal regimes and usually require large volumes with slow response times. Closed loop food production and nutrient recovery from waste can only be provided by biological processes employing living organisms in plant cultivation which is volume intensive. Closed biological regeneration involves the production of food, recycling of waste, recycling of water, and air regeneration.

13.2. CLOSED ECOLOGICAL LIFE SUPPORT SYSTEM

Algae are efficient producers of oxygen but unpalatable as food. Higher plants however also produce oxygen and remove carbon dioxide by photosynthesis, purify water through transpiration and are easily digestible as food. Wetland and marsh microbial creatures can process waste and metabolise contaminant pollutants. Enzyme bioreactors are utilised by the food and pharmaceuticals industry and are well-suited to carbon recycling in closed life support systems, eg. cellulase degrades cellulose into its components such as edible glucose. Such enzymes may be fixed to a solid medium for shear force resistance through encapsulation in a small artificial cell or liposome [Tamponnet et al 1992]. Enzyme bioreactors can generate amino acids, fatty acids and vitamins. Micro-organism bioreactors such as bacteria, fungi, yeast, and algae can recycle all the major biochemical elements and degrade complex organic molecules in waste into usable materials. They require oygen and large volumes. Microbial bioreactors such as bacteria fixed to a filter bed can also act as biofilters to filter air. Higher fungi such as mushrooms can be grown on a solid substrate like straw without the need for light. Higher plants are required for food with rice, wheat, soyabean, peanut, corn and potatoes being the most favourable. Plant cell cultures may be used for plant propagation, but may not be genetically stable. Plants require carbon dioxide and nitrogen from the microbial degradation of waste. Small animals may be bred such as worms which can grow on solid wastes. High protein flour can be obtained from drieed worms: a 300l soilbed can yield 60-80kg of flour per year. Worms can provide food for fish which offer high food value. Around 500kg of catfish can be grown an a 1m^3 tank per year but fish-breeding requires lighting. In 1977, NASA began its Controlled Ecological Life Support System (CELSS) programme which culminated in the Biosphere 2 project in Oracle, Arizona. A chief difficulty lies in the fact that ~10-25m^2 of plant cover is required for food for one person and such areal cover produces 1.5 times the required oxygen and 5 times the water requirements for one person, making this inefficient. Furthermore, the balance between the amount of oxygen and the amount of carbon dioxide produced as a consequence of metabolic activity is ~0.84-0.87 depending on the percentage formation of carbohydrate, fat and protein in the food consumed. The chief interest in such systems is the relevance to recycling and regeneration on Earth [Huttenbach 1992]. Such application technologies include the reduction of resource consumption and recycling waste with material closure. Farmers have in the past concentrated on improving crop yields without considering the overall impact on the environment from the excessive use of fertiliser, excessive consumption of water supplies and the attendant run-off of waste materials. These considerations are taken for granted and are difficult to quantify without specific detailed research such as Biosphere 2.

Life support systems require considerable investment as safety critical functions. Atmospheric parameters – temperature, pressure, composition, contamination – must be controlled to ensure both physiological compatibility and comfort. Physico-chemical atmospheric recycling based on the absorption of CO_2, catalytic reduction and water electrolysis to generate O_2 is well established. Water for both consumption and hygiene must be managed and recycled. Food must be stored and preferably produced locally. Human waste must be processed to minimise loss of useful material while ensuring that waste as a poison does not threaten the crew's health. Bioregenerative life support is currently under investigation through the European MELISSA (Micro-Ecological Life Support System Alternative) – this is based on microbial bioreactors for the treatmemt of organic waste and the generation of nutrients, water and oxygen. The safety of the crew to accident and environmental dangers such as radiation must be maximised. Finally, crew psychology may be one of the most difficult issues to contend with – astronauts will not function effectively for the mission unless they retain high motivation.

13.3. HUMAN HIBERNATION

The induction of hibernation in human crews for long duration missions to reduce resource supply is an alternative to closing life support system cycle. The human Mars reference mission assumes a six-man crew to fly to Mars in a period of 6-9 months, explore the surface for around 500 days, and return to Earth over another 6-9 months. Water is the critical resource (as it can be also be used for breathing oxygen) of which some 30 tonnes with 10% recycling for just 200 days would be required (dropping to 10 tonnes with 90% closure). The development of in-situ resource utilisation techniques such as water mining solves the problem of survival on the Martian surface but not the problem of water storage and transport in transit. The only solution is to reduce the life support resources during transit – this as a side effect would solve significant psychological problems associated with long-term isolation. Hypermetabolic stasis involves significant reduction in metabolic rate and so physical resources for powering that metabolism. Bacterial dormancy is well established – viable halophilic bacteria have been recovered from salt lakes some 250 millions of years old [Adams 2000]. Such capabilities are unlikely to be of applicability to human crews. However, in animals, the five states of dormancy are: sleep, winter sleep, torpor, aestivation, and hiberation. Some mammals such as ground squirrels which enter hibernation or torpor exhibit body temperatures which fall from 37°C to under 10°C (even as low as –3°C in some cases). During sleep, the human brain is highly active such that sleep deprivation leads to severe behavioural defiiciencies and even death [Harrison & Horne 2000]. Hence, induced sleep will yield little reduction in metabolic requirements. Some large mammals such as bears, badgers, raccoons and opossums, exhibit prolonged sleep in winter without a drop in body temperature. Hence, winter sleep is unlikely to solve the problem of reducing metabolic rate. Torpor is a stage passed through from sleep to hibernation during which body temperature reaches close to ambient temperatures. Winter hibernation occurs in 50% of mammals (including primates but rodents and insectivores in particular) suggesting that all mammals possess the basic mechanisms for hibernation with a consequent reduction in metabolic requirements. Aestivation – summer torpor – involves the formation of physical barriers to arid conditions, eg. burrows, cocoons, etc in conjunction with increased water retention. It is similar to hibernation but occurs in summer. One essential requirement during hibernation will be automatic monitoring and diagnostic facilities, eg. Guardian for intensive-care patients [Larrson et al 1998]. Such a facility will be required to induce, maintain, and end the hibernation state according to the situation, almost certainly augmented by ground control.

We do not consider human life support and hibernation technologies further in this report other than to note that it is not considered a near term technology.

14. Conclusions

Complex adaptive systems are systems in which complex global behaviours emerge from the interaction of large numbers of simple components [Mitchell 1993]. Examples include genetic algorithms and immune system models. Genetic algorithms model reproduction with variation (due to sexual reproduction) and selection through a fitness metric. In the immune system, antibodies attack antigens to which they can bind generated through clonal selection. The GA can model this through evolution of high binding strength antibodies. The lamprey's adaptive immune system is based on a different genetic building block characterised by leucine-rich repeats. Neuro-endicrine approaches may be modelled as an artificial neural network augmented with an adrenal gland. The network learns the dynamics whilst the adrenal gland influences the pre-trained weights within the network by reeasing an artificial hormone when excited by off-nominal dynamics. Artificial life is a variant on genetic algorithms in which an ecological community (Tierra) of self-replicating programs (digital organisms) was evolved from a single ancestral self-replicating program by copying themselves with mutations and competing for computer processor time and memory space. Parasites which take over the copying mechanism of prey, hyperparasites which resist parasites evolve in an arms race of increasing sophistication. Biomimetics represents the first steps towards complex adaptive systems in engineered systems. There are a number of possible applications of biomimetics to spacecraft engineering problems, most of which have not been discussed, some of which are listed thus:

- Velcro fastening
- Self-cleaning lotus/aspen effect (*Populus tremula*)
- Low-drag shark skin
- Gecko-foot adhesion
- Fibre-optic properties of silica sponge spicules
- Bacterial mineral processing
- Trabecular bone-like materials
- UV protection by aromatic pigment biomolecules
- Spine/snake-based manipulators
- Self-repair through reconfigurable cellular units
- Plant-like or cell-like tensegrity structures
- Leaf-folding and insect spiral compaction for deployable structures
- Passive flight, eg. sycamore seeds
- Passive land locomotion, eg. tumbleweed/wheel analogue
- Squid jet propulsion
- Bomardier beetle combustion
- Thermal regulation by penguin down and polar bear fur
- Electronically controlled insects
- Ant social behaviour
- In-situ resource utilisation/ecologically closed regenerative life support using anaerobic and aerobic bacteria or enzymes

Given that the number of potential biomimetic solutions to engineering problems are to all intents and purposes infinite, we have adopted a structured approach whereby biomimetic approaches have been mapped to specific robotic spacecraft subsystem technologies. There is little doubt thatr biomimetic approaches have much to offer space systems in terms of enhanced functionality within packages of reduced mass. The chief obstacle to their implementation will be the space community in their insistence on illusions of complete controllability of traditional spacecraft engineering techniques. For instance, software systems are usually only partially tested and deterministic behaviour cannot be guaranteed. This situation is little different from that implied by biomimetic-based technology. However, there are problems that cannot yet be handled by machine: Type 1 problems are those which offer regularities within input data while Type 2 problems are those which require re-coding of input data, the latter being difficult to solve [Clark 1997]. However, biomimetics has much to offer the spacecraft engineer in that biology is constrained similarly by limited resources, mass, volume and energy and has provided designs within those constraints often exploiting principles that the engineer rare;y if ever uses. There are a number of specific technologies that are highly suited to space application – genetic programming, evolutionary hardware, etc - as outlined in this document which have immediate utility. In conclusion, biomimetics is a rich area for further investigation and analysis which may offer the potential for massively increasing the functionality of spacecraft with little or no impact on mass.

Appendix A: Neural Networks

ANN’s (artificial neural networks) are artificial analogues of neural architecture of the human brain. The brain is a massive parallel device of 10^{11} neurons each with 10^{3} synaptic connections. The connection scheme is much less than that required for a crossbar switch which would otherwise make the fan-in and fan-out impossibly large ~10^{22}. Neural networks are physical devices that embody transformation functions for sensorimotor integration of behaviour. Artificial neural network transforms sets of input signals into sets of output signals. Neural networks or parallel distributed systems modelled on the brain's hardware (with a high degree of simplification!) offer a method of learning input/output pairings. The brain is a massively parallel device of layers, the unit of which is the neuron acting as a random access memory. It has no scheduling programs. Indeed it has been called into question whether symbol-processing is an adequate description of human cognition particularly with regard to learning and skill acquisition. Neural networks are sets of interconnected neurons which send excitatory or inhibitory signals to each other through the network. They do not store discrete symbols but store information implicitly as patterns of activity over sets of neurons. Each individual symbol corresponds to differing patterns of activity. All neurons operate concurrently and since knowledge structures are processed in parallel, different sources of knowledge simultaneously influence each other interactively providing the means for simultaneous mutual constraint satisfaction. Activation level of a neuron is a function of its different inputs (positive along excitatory links and negative along inhibitory links). Different inputs are weighted and the neuron sums all weighted input. Connection weights determine activation levels and determine the information processing storage mechanisms. Knowledge is represented in a distributed manner such that each neuron may respond to a number of different inputs. This allows content addressibility whereby partial information can generate complete descriptions of concepts from memory rather than requiring searches by location addressing for information retrieval. The learning process corresponds to modification of connection weights between neurons.

The synaptic links between neurons are unidirectional and each has an associated connection weight w_{ij} forming a nonlinear network of intercommunicating elements. The values of the connection weights are obtained by learning from a set of training patterns. Information flows along the synaptic links which attenuate or amplify the signals according to the synaptic weights. The number of synaptic inputs per neuron is typically large but each neuron has only a single axonal output which fans out to serve as input to other neurons. The numeric weights modulate the activation of the neuron whereby the neuron integrates incoming signals. Each neuron possesses a particular activation state x_i and the synaptic weight w_{ij} defines the effect of neuron j on neuron i. The synaptic connections may be excitatory which increases the activation level of the receiving neuron or inhibitory which decreases the activation level of the receiving neuron. The weighted sum of inputs is passed through a nonlinear function to derive the output. Each neuron is thus characterised by weighted synaptic inputs, a summation function (and often a threshold level) and its axonal output connections. Neural activity is a function of the activity of other neurons that synapse on it and its internal biochemical state. A model of the neuron had firing frequency output as a nonlinear function of the neuron’s potential. A linear saturating threshold function provided an initial discontinuity in firing. The ANN is driven by the activation that passes from unit to unit. Different units simultaneously influence each other and mutually constrain each other as the output from other units affect the receiver unit according to the connrection weights. This mutual constraint satisfaction occurs in parallel by parallel activation due to simultaneous communication of excitatory and inhibitory signals. This activation is “subsymbolic” and each neuron acts as a classifier accounting for their usefulness in pattern recognition. The amount of output activation depends on the extent to which a feature is present in the input. Large numbers of neurons offer high redundancy and graceful degradation and fault tolerance.

The ANN can operate in two modes – learning machines and associative memories. Learning procedures in neural networks discover internal representations by modifying connection strengths with gradient descent methods according to computation of error derivatives with respect to the connection strengths. This learning corresponds to modifying the plastic nerve connections in the brain. Weights encode regularities in input-output mappings through generalisation. Simple associative nets have input units connected directly to output units. The neurons and synapses comprise the hardware of the network while the weights and threshold are the software. Programming the network involves adjusting the weights and threshold. Learning accomplishes this automatically. Once the connections are learned, they may become rigid. ANN's are associative memories in that they store information and they learn to associate different sensory patterns through repeated presentations of stimuli to trigger responses. Associations can be stored by the convolution operation and retrieved by a correlation matrix between the key vector f_j and associated vector g_j. If pattern f and pattern g are associated they may be represented by $\delta w_{ij} = \eta f_i g_j$ where η=learning parameter. The weighting is proportional to the pre- and post-synaptic activity. The weighting matrix W defines the association of the network in the form $W = gf^T$ [Anderson 1983]. For more than one pattern $\delta w_i = g_i f_i^T$ so the overall synaptic connectivity matrix is given by $W = \sum_{ij} g_i f_j^T$. This is a holographic property though not of the Fourier transform variety. Holograms are generated by interference patterns offering nonlocal, parallel information storage with fault tolerance and reliability. Output patterns may be generated as the product of the connectivity matrix w_{ij} and the input pattern $g_i = f_i \sum_{ij} f_j^T \sum f_j$. Associations are stored by correlation, ie. superposed interference patterns distributed across the network as a covariance matrix $f_i f_j$. Signals set up standing wavefronts in neurons which interact and interfere in overlapping synaptic junctions. Different features have different neural encodings for classification and categorisation. Representations of stimulus-response associations are content-addressable rather than location-addressable as in conventional memory where each possible input address selects a unique location at which the contents reside. When the network is activated by an input pattern that is close to the stored pattern in the network, the system will rapidly converge to the complete stored pattern thereby recalling it – this is the associative content addressibility which uses a key portion of the memory contents. Associative recall may be represented as: $g_j = f.W = f.\sum_j g_j f_j^T$. Neural activation pattern is the representation of the environmental state distributed across all neurons. The activity potential of a neuron acts as a crude memory and an inhibitory connection back to itself provides negative feedback to effect an exponential decay in activity potential $p = p_0 e^{-kt}$ where k=decay constant which determines the recovery period [Feldman & Ballard 1982]. The activation level defines STM while LTM is encoded in the interconnection pattern defined by synaptic weights. Patterns of activation refer to a given environmental input state. Different activation patterns can potentially generate the same outputs. Similarly, different outputs may be generated by the same inputs. Hence, ANN's are not simple stimulus-response systems – it is not valid therefore to infer internal representation states from the observed outputs. The ANN represents the massively parallel distributed approach to computation which is essentially a nonalgorithmic form of information processing where emergent computational properties arise spontaneously. This is a powerful computational paradigm. If implemented in VLSI hardware they offer rapid real-time capability and robustness. VLSI technology ~0.25μ could yield around 10^9 interconnections with 10^6 processing elements on a single chip exhibiting 10^6 speedup in operation [Wah et al 1989]. The size of a network is related to its application – above n=1000 input neurons an optical or optoelectronic implementation is necessary. ANN's may be of the feedforward type without feedback (eg. the perceptron) or of the feedback type (eg. the Hopfield net). Information flow in feedforward networks is unidirectional and provides a static nonlinear map between the input and output. The neurons are arranged in layers with connections being formed between the layers only and inputs propagate and interact in one direction to produce the output. They tend to be characteristic of peripheral nervous system. Feedback nets are undirected graphs with bilateral connections. In formation flow is recurrent with feedback relations so that the state of any neuron is an indirect result of its own previous activity state. They simulate asynchronous (sequential) computers in that they evolve from an initial input state to a final output state though synchronous (parallel) operation is also possible.

Artificial neural networks emulate the function of the brain, although on a much smaller scale – the human brain comprises 100 billion neurons each connected up with around 10,000 others. All biological neurons are cells comprising four basic components: dendrites, soma, axon and synapses. Dendrites are input channels which receive input from synapses from other neurons. These are weighted. The soma processes these input signals by summing the weighted inputs, feeding them through a transfer function (typically a sigmoid or a hyperbolic tangent to provide a binary thresholding operation). The soma outputs the result through the axon to other synapses from other neurons. The neural network is clustered into networks or groups, typically 3-4 layers to separate input, hidden and output segments. Lateral inhibition typically resides in the output layer. There are two approaches to training neural nets – supervised training in which performance is graded accorded to the desired output (most common), unsupervised training in which the network clusters the input. Initially the network should be given non-zero random weights. The McCulloch-Pitts neural network may be configured as a universal Turing machine and so implement any program. The McCulloch-Pitts neuron may be modelled with output:

$y_i = f\left(\sum_j^N w_{ij}x_j\right)$ where x_j =input of neuron j

w_{ij} =weight between neurons i, j

The threshold f is step function to yield a digital output:
f(x) = 1 if x>f
-1 otherwise (-1 yields possibility of decrement to weights as well as increase of weights)

Other functions include linear function: f(x)=kx or sigmoid function $f(x) = \frac{1}{1+e^{-kx}}$ for $0 \le x \le 1$ or tanh(x) for $-1 \le x \le 1$.

The sigmoid function squashes the function where k controls the shape of the response. When k→∞, it generates a stepping function. In recurrent neural networks (as opposed to feedforward neural networks) the network has feedback connections between layers or within layers. Initially, random small weights are adopted. Recurrent neural nets are universal computers. Learning involves repeated presentation of input-output pairs (for supervised learning) or input patterns only (for unsupervised learning) and adjusting the weights:

$$w_{ij}^t = w_{ij}^{t-1} + \eta \Delta w_{ij}^t$$

Hebbian learning associates presynaptic and postsynaptic neurons by: $\Delta w_{ij} = y_i x_j$

Supervised learning reduces the error between the desired and actual outputs for a given input pattern. For one interconnection layer, delta rule is given by:

$y_i = f\left(\sum_j^N w_{ij}x_j\right)$ where f(x) is linear function

Delta error is given by: $\delta_i = (y_i^d - y_i)$

Weight modification is defined by: $\Delta w_{ij} = \delta_i x_j$

Training patterns are presented several times in random order and the delta rule minimises the error function:

$E = \frac{1}{2}\sum_j^m \sum_i^n (y_i^d - y_i)^2$ where m=total number of training patterns

n=total number of output neurons

Delta rule requires knowledge of the correct response for each input training pattern. Single interconnection layer networks can learn only linearly separable mappings. The perceptron cannot express nonlinear decisions such as the XOR function which is not linearly separable into two parts but requires linear separability three parts. Indeed, according to the Stone-Weierstrauss theorem, a two layer network with an arbitraryily large number of nodes in the hidden layer can approximate any continuous function $f \in (R^n, R^n)$. The hidden layer divides up the input space with hyperplanes defined by its weights:

wx+b=0 where b=threshold.
w=weight
x=input vector

The number of hyperplanes is equal to the number of nodes in the hidden layer. In d-dimensional space, the number of hidden layers H=M-1 for d=1, and H=log$_2$M for H≤d where M=maximum number of linearly separable regions [Mirchandani & Cao 1989]. In supervised learning, the input-output pairs of the training set are provided and performance is compare with the desired outputs, the error being propagated back to adjust the weights (backpropagation of error). This is a version of the Widrow-Hoff least mean square of error rule which adjusts the weights along the negative gradient to minimise the error function. The training set should be presented in random order. Most ANNs use multilayer backpropagation which can learn the nonlinear dependencies between input and output. In fact, the backpropagation algorithm evaluates the transpose of the network Jacobian at the network's input vector by computing partial derivatives of the error criterion with respect to the weights and may be derived using a Langrangian formulation as used in optimal control. Unsupervised training involves presenting the inputs (but not the outputs) with the system deciding which features are used to group the input data. Pattern classifier (associative) networks take an input vector and outputs a value that determines its classification. The most common associative network is the recurrent Hopfield network whereby its outputs are fed back to the inputs, ie. a single layer. For patterns which are not linearly separable such as XOR function require a two interconnection layer network with a set of hidden units and the output units must be nonlinear, eg,. sigmoid function. The delta rule must be modified to cope with the hidden layer. The backpropagation of error method is a generalised delta rule which implements a type of Moore-Penrose pseudo-inverse:

Hidden unit values, $h_j = f\left(\sum_{k=0} w_{jk}x_k\right)$ where f(x) is sigmoid function

Output values, $y_i = f\left(\sum_{j=0} w_{ij} h_j\right)$

Compute delta error with first error derivative due to use of non-linear activation function,

$$\delta_i = \dot{f}\left(\sum_{j=0} w_{ij} h_j\right)(y_i^d - y_i) \text{ where } \dot{f}\left(\sum_{j=0} w_{ij} h_j\right) = y_i(1 - y_i)$$

Delta error of hidden units is computed by propagating delta errors backwards through connection weights:

$$\delta_j = \dot{f}\left(\sum_{k=0} w_{jk} x_k\right) \sum_i w_{ij} \delta_i$$

Weight changes of two layers include delta errors:

$$\Delta w_{ij} = \delta_i h_j$$

$$\Delta w_{jk} = \delta_j x_k$$

Weights are updated:

$$w_{ij}^t = w_{ij}^{t-1} + \eta \Delta w_{ij}$$

$$w_{jk}^t = w_{jk}^{t-1} + \eta \Delta w_{jk}$$

Every pair of input-output patterns in the training set is presented several times in random order until total sum squared error is given by:

$$TSS = \tfrac{1}{m} \sum^{m} \left(\tfrac{1}{N} \sum_i^{N} (y_i^d - y_i)^2 \right) < \varepsilon$$

Typically, the ANN comprises of a number of layers of neurons. At the output layer, neurons' outputs are compared with desired values representing a classification pattern from training data set. If there are differences, the error can be decreased. The nonlinear dynamics of the neural network system may be characterised as a potential energy-like Lyapunov cost function:

$$E = -\tfrac{1}{2} \sum_i^n \sum_j^n w_{ij} x_i x_j - \sum_i^n \theta_i x_i$$

State transitions of neuronal activations represent a trajectory of states. For stable inputs, the ANN will assume a stable state of fixed points or limit cycles. The Lyapunov function may be regarded as a generalised Hamming distance of the state vector from the stable equilibrium points. It has many equilibrium points which define the energy wells on the energy surface in n-dimensional hyperspace. Each point on the energy surface corresponds to a pattern of activation of neurons. The energy landscape is a function of synaptic weights w_{ij} and the weights determine the effectiveness of transmission of the synapses. There are 2^n possible neural states and the network dynamics produces a path through the state space that tends to minimise the energy cost function. The energy minima store information as memory association patterns in a distributed Gestalt sense. A large positive connection weight corresponds to low energy. The more the stored information is retrieved the deeper the energy minima. Weight update performs a gradient descent of the energy function. The network configuration follows an optimisation procedure to find optimal solutions [Hopfield & Tank 1986]. The synaptic weights determine the flow of neuronal activation and neuronal state transitions. This effectively relates the inputs and ouputs to each other.

A data sample may be represented by (x,y) where a smooth function maps between the inputs x and outputs y=f(x) + ν where ν=noise. Input neurons may be connected to the outside environment each of which responds to a narrow range of parameter values (receptive field). The simple neuronal processing units are interconnected to form a network. Neurons act as selectively tuned filters to particular signal patterns. The neurons are heavily interconnected so that the neural network acts as a directed graph with weighted edges. Networks of McCulloch-Pitts neurons are devices capable of Boolean logic using AND, OR, NOT operands – they are the simplest form of layered feedforward networks which are composed of discrete three-valued McCullough-Pitts neurons (neuron activity of +1, -1, 0 representing true, false and unknown respectively). They are all-or-nothing discrete neurons representing discrete action potentials giving binary output. This allows the use of thrshold logic. Each neuron receives input from every output in the preceding layer. Each neuron stores only a single scalar value, so individual neurons do not transmit large amounts of symbolic data. If the system is digital, the input and output vectors may be represented as vector strings of 0 and 1's. Two values are either the action potential voltage (1) or the resting potential voltage (0). Each neuron has a given level of activity and sends this value as output down all their output connections. Each unit computes the nonlinear weighted sum of their positive (excitatory) and negative (inhibitory) inputs. The output function is a sigmoid function about a threshold.

The neuron state is the input to neuron i as a function of activity level of inputs to i:

$x_i = -\theta_i + \sum_{i,j=1}^{n} u_j(t) w_{ij}(t)$ where θ_i =threshold bias current

w_{ij}=synaptic connection strength

u_j=input state to neuron

Output state is given by a nonlinear sigmoid input-output function: $y_j = f(x_j) = \frac{1}{1+e^{-x_j/\rho}}$.

The function f is related to response mapping rules such as the firing frequency of the neuron to its membrane potential. The parameter ρ determines the shape of the sigmoid – a larger value gives a flatter curve. The sigmoid function is a squashing function is used to describe the input-output characteristics of each neuron. Another typical sigmoid function is:

$y = \tanh(x(k) = \frac{1-e^{-2x_k}}{1+e^{-2x_k}}$ which is normalised so that saturation occurs as $\rightarrow \pm 1$.

The sigmoid function is a continuous squashing function to enable the output of real positive numbers. The sigmoid function takes on the values $\pm s$ when $x \rightarrow \pm\infty$. The sigmoid function acts as a linear filter when the output is small and saturates to $\pm s$ when the outputs are large. Such a sigmoid function is capable of forming internal representations more complex than simple binary codes and provides Gaussian smoothing. Each unit's output is a function of its activation level. Interneuron signals comprise of single scalar values in a value/marker passing system. Multiple instances of scalar values are weighted and ANDed into a sum and processed by the nonlinear output function. As the activation of a single neuron is a nonlinear function of the sum of weighted inputs, a given activation can be realised by different summation terms. Two different environmental states may generate the same activation of a given hidden/output neuron. Information is represented in the connection weights between the processing units in the network forming an activation pattern, ie. distributed over the network. The ANN is based on causal connections as the primitive relations between nodes. The distributed representation involves the extraction of subsymbolic "microfeatures" representing a statistical properties of the input-output relation of training data. Each node represents a subsymbolic representation of "microfeatures". Each unit may participate in the storage of many different representations with abstract microfeatures stored at the neural level. The threshold may realise formal Boolean logical functions. A high threshold generates an AND response while a low threshold acts like an inclusive-OR function. Hence, any process which can be described by formal logic may be encoded in such formal neurons. Each unit is activated if and only if its total excitation exceeds zero. Activity potential may be disjunctive (OR) or conjunctive (AND). Formal nets are synchronous and switch only at discrete levels and are equivalent to Turing machines. The function f is a nonlinear activation function usually an input-output sigmoid function which provides a nonlinear output as a function of the neural states. This simulates an integrative time delay of neuron capacitance C_i and membrane resistance R_{ij} characteristic of brain cells, ie. the time delayed RC charging function of neurons. The neuron acts as an input-output transducer of differential equation form and the integrator acts as a delay operator.

SUPERVISED NEURAL NETWORKS

Rate of learning using a supervised technique is much faster than that for an unsupervised technique. Usually a supervised learning scheme is used first to learn as much a priori information as possible and then an unsupervised learning sheme is used online to improve learning rates in an unstructured environment [Fu 1986]. Learning is enabled through weight changes and the strength of the synaptic links between neurons is determined by an learning/update algorithm, eg. the steepest descent multiplayer perceptron backpropagation algorithm trains the network from examples for pattern recognition and matching [Lecher et al 1992]. The learning phase performs iterative updating of the synaptic weights based on a learning rule. Thus information processing comprises mapping input to output data by modifying connection weights. Learning algorithms determine the degree of synaptic weight changes during learning and are derived from input-output data:

$w_{ij}(k+1) = w_{ij}(k) + \eta\delta w_{ij}(k)$ where η=learning rate parameter= $\frac{k}{\sqrt{\sum\left(\partial E/\partial w_{ij}\right)^2}}$

k=stepsize which alters the speed of convergence

It was found that the efficiency of learning is dependent on the incremental connection weight δw- if too small, learning is slow and if too large, overshoot occurs leading to the condition [Ainsworth 1967]:

$$\left(\frac{m}{m-1}\right)\left(\frac{d}{n}\right)\left(\frac{w_1-w_2}{2}\right) \le \delta w \le \left(\frac{m}{m-1}\right)\left(\frac{d}{n-d}\right)\left(\frac{w_1-w_2}{2}\right)$$

where d=minimum Hamming distance such that $1 \le d \le n/2$
m=number of output neurons
n=number of input neurons

The incremental connection weight δw may be regarded as a reinforcement signal $r_I(t)$. The learning rule involves credit assignment to find the set of synaptic weights to optimise a performance function E based on training patterns. Hebb's rule states that the weights change in proportion to the outer product of input and output, ie. Hebbian learning is a linear association between i^{th} input unit and j^{th} output unit: $\delta w_{ij} = u_i(k)u_j(k)$

Weight modification depends on presynaptic and postsynaptic activity. Weights in this case are equilibrium states that encode cross-correlations between input and output states of the network. The Hebbian learning procedure reproduces many of the properties of neuronal receptive fields in the visual cortex, including centre surround fields and orientation columns. However, it cannot produce the temporal characteristics of classical conditioning.

It is desirable with neural memory storage to minimise a measure of the differences between desired output vectors and actual output vectors when adjusting connection weight changes during learning:

$$E = \tfrac{1}{2}\sum_j (y_j - y_j^d)^2$$

so that weight changes are $\delta w_{ji} = -\eta \frac{\partial E}{\partial w_{ji}}$ where $\frac{\partial E}{\partial w_{ji}} = \frac{\partial E}{\partial y_i}\frac{\partial y_i}{\partial x_j}\frac{\partial x_j}{\partial w_{ji}} = (y_j - y_j^d)\frac{\partial y_j}{\partial x_j} y_i$

η =learning rate

This is a least squares error minimisation in the multidimensional "weight-space" which performs a gradient descent in the error surface to a single global minimum (for directly connected input-output units). It assigns credit to input units to their activation level. Alternatively, a threshold least squares procedure may be defined as $\delta w_{ji} = -\eta \frac{\partial E_j}{\partial x_j} y_i$.

The perceptron is a neural network of formal neurons comprising a layer of sensory inputs connected directly to a layer of motor outputs with trainable connections [Rosenblatt 1958]. To learn input-output mappings, it uses a convergence algorithm which ignores the magnitude of error by changing the weights by ε to give a binary response:

$\delta w_{ji} = \eta y_i$ if output is on

$= -\eta y_i$ if output is off

This provides a means of reducing the squared distance in weight space $(w_i - w_i^d)^2$ rather than reducing least squared errors of outputs. A major problem with simple input-output layer associative networks is that they cannot compute functions such as xORELSEy and particularly ~(xORELSEy), ie. EX-OR or EX-NOR which are computationally universal (ie. Turing equivalent). Exclusive-OR problems cannot be solved using two layer networks but can be solved with network employing hidden units between the input and output layers through an “internal representation”. A two layer network system can only realise simple threshold logic functions AND/OR/NOT/NAND/NOR. Universality requires the addition of hidden layers within the net generating the problem of credit assignment to the hidden layer. Hidden units between the input and output layers provide intermediate abstraction as patterns of activity. The number of hidden units is an important parameter of the network, as too few underconstrains the problem with too little structure to extract the required abstractions and too many overconstrains the problem destroying its generalisation capability. Such hidden units act as input property detectors. The input layer acts as a feature detector while the hidden units t’y to combine th’se features to generate the correct output. Neither Hebb's or Rosenblatt's learning rules can be used for multilayer nets with hidden units. The multilayer perceptron is a feedforward type of neural network which use– a supervised learning algorithm to compute complex nonlinear functions - this is the error backpropagation algorithm which is a generalisation of the least squares error procedure. The backpropagation algorithm backpropagates the error between the desired and actual node activation levels through the network during learning. It allows the network to learn arbitrary nonlinear characteristics between input-output data pairs through training. The MLP network may thus be regarded as a nonlinear mapping function N(u). The connection weights encode patterns which indicate the statistical properties of the network. The negative of the gradient of the squared error indicates the direction of fascent descent to decrease the error. Backpropagation finds the trajectory through the set of states from the initial to terminal state. The difficulty is the existence of local minima that can trap the solutin process. Weights are adjusted until the network can match all training examples [Low et al 1990]. Weight decay may be introduced into the rror function so that the weight decays to zero in prportion to its magnitude. This helps to overcome overtraining the network which causes loss of generalisation ability by over-fitting data. In other ways the MLP network may be regarded as a two layer perceptron. Hence, the backpropagation algorithm network comprises of an input layer, an output layer and at least one hidden layer which has no direct contact with the outside world. As full connectivity of hidden neurons inhibits learning, hidden units within the same layer may be clustered according to the similarity of their input weight vectors [Fu 1993]. This allows compaction of encoding in the hidden layers. Thus ANN's can perform Boolean operations so they are formally equivalent to the universal Turing machine. According to the Weierstrauss theorem, any function can be approximated by a polynomial. An extension of this, the Stone-Weierstrauss theorem states that any arbitrary nonline'r function can be represented as a Volterra or Wiener series. Kolmogorov's neural analogue to this is that there exits a three-layer ANN which can produce an arbitrary nonlinear operator equivalent to a generalised spline function specified by example input-output pairs.

LEARNING RULES

The backpropagation algorithm is an iterative gradient descent algorithm to minimise the mean square error between the actual output of the multilayer perceptron and the desired output. The backpropagation algorithm can compute derivatives $\frac{\partial E}{\partial y_i}$ for all units including their hidden units. It uses an objective performance function as the summation of square errors between the desired outputs and the network outputs over the integral time t:

$$J = \tfrac{1}{T} \sum_{i=k-T+1}^{k} (y^d - y)_i^2$$

where $y = f(\hat{x}_k, w(k)) = \sum_{j=1}^{n} w_j(k) x_j(k) ==$weighted input vector

$y^d = f(x(k))=$desired output response=teacher input signal

This is a normalised Hamming distance function or generalised least error squares rule which reduces the error. The backpropagation algorithm performs credit evaluation and credit assignment in determining how the hidden neurons contribute to the network outputs and how they affect the measurable errors respectively [Jones & Hoskins 1987]. In the backpropagation algorithm scheme two passes are required each time an input is presented. The forward pass begins at the input units to compute the activity levels of all units in the network to produce an output vector. The output response is compared with the desired response to generate the error signal. The backward pass starts with the output layer and works backwards in the reverse direction to compute the derivative of the error $\frac{\partial E}{\partial y_j}$ for hidden units j from the output units k:

$$\frac{\partial E}{\partial y_j} = \frac{\partial E}{\partial y_k} \frac{\partial y_k}{\partial x_k} \frac{\partial x_k}{\partial y_j} = \frac{\partial E}{\partial y_k} \frac{dy_k}{dx_k} w_{kj}$$

Errors are thus propagated back from the output units to assign credit to each connection weight for each layer until the input layer is reached. Training alters the weights of the neurons to alter the behaviour of the network to capture the regularities of the input-output function. The weights are effectively the system parameters that are adjusted for adaptive lea–ning. The error surface idicates that hidden units contain local minima - ie. it is the hidden units which represent internal abstractions of concepts from the outside world (the initial weights of the hidden layer are chosen randomly). The hidden units and their interactions extract the regularities in the input-output mapping.The gradient of the output error with respect to each weight determines the weight change. Weights are adjusted according to the steepest gardient descent rule to reduce that error in the weight space of possible representations:

$w_{i+1}(k+1) = w_{ij}(k) - \eta\left(\frac{\partial J}{\partial w_{ij}(k)}\right)$ where $0.1 < \eta < 1.0$, eg. $w_{i+1}(k+1) = w_{ij}(k) - \eta[z(t) - y(t)]x_i(t)$ where $y(t) = \sum_{j=1}^{n} w_j(t)x_j(t)$

z(t)=teacher input

This is the Widrow-Hoff delta rule which is a Markov process with a stationary distribution and peaks at the local minima of J. Once the asymptotic value of z(t) is reached, we have the Rescorla-Wagner model of classical conditioning. Desired output may be regarded as a supervised teacher signal. Function y is a feedback representing expectation as a weighted average of past values of the output. The change in the weight parameter $w_{ij}(k)$ by backpropagation is given by $\delta w = w_{i+1} - w_i$ produces a change in the output y(k+1):

$$y(k+1) = f(y(k), y(k-1)) + u(k)$$

The steepest descent search is thus used to acquire the minimum of the objective function J to determine which connection weights need to be strengthened or weakened to yield the optimal weight parameters based on the output errors (between the network output y and the desired output y^d) derived from the input-output pairs (ie. it is an error correction rule). Associative reward-penalty learning rule has the following form:

$$w_{ij}(t+1) = w_{ij}(t) + c_r\left(r(t)x_j(t) - \left\langle x_j(t) \left| \sum_{i=1}^{d_j} w_{ij}(t)x_i(t) \right\| \right\rangle \right) x_i(t)$$

where c_r=asymmetric gradient for r(t)=+1 and r(t)=-1 such that $c_{+1} > c_{-1}$.
It is this asymmetry between reward and penalty gradients that different A_{RP} from the Widrow-Hoff rule.

The training patterns are repeatedly clamped to the input and output layers until I satisfactory performance is achieved. The procedure is in two phases: (i) clamp the input vector to the input layer and the output vector to the output layer and then increment the connection weights that have both input and output terminals active; (ii) clamp the same input vector to the input terminal and let the network determine the output and decrement all connections that have active input and output terminals. This process is repeated for all input-output pairs [Hinton 1985]. The recommended number of training steps are ~1000 times the number of processing elements. Only once the network has been trained can it be used for real-time processing as the processing time is independent of the number of patterns stored and the information storage per pattern. The gradient descent provides the means for the network to self-organise by approximating to the input-output function to improve its performance over time without knowledge of dynamic equations. The output of the updated network approaches the output of the function to be approximated for the same input x(k) if η is small and the average error $\frac{1}{n}\sum_{k=1}^{n} J_k$ decreases and converges as n gets large. This is the process of self-organisation of the network. The ANN forms a representation of closed excitations at different positions of the neural field which comprises a two-dimensional map of the network (cortical map).

The backpropagation algorithm is a generalised delta rule which may have biological plausibility. The backpropagation and learning procedure is however slow. If each output vector is regarded as a conditional probability distribution over a set of outputs given an input, backpropagation finds weights to maximise the likelihood of generating the desired conditional probability distribution. Hidden units should be connected to only a small region of input units but to many widely separated output units. The minimised function then becomes the cross-entropy C between the desired and actual conditional probability distribution rather than squared error:

$$C=-\sum_j y_j^d \log_2 y_j + (1-y_j^d)\log_2(1-y_j)$$

In fact least squares minimisation and maximum likelihood estimation are equivalent, though gradient descent is faster than least squares adaptation.

HOPFIELD NET

Feedback networks include the Hopfield recurrent net where the input information defines the initial activity state of the system. The Hopfield network is an autoassociative feedback neural network of neurons whereby the outputs of the neurons are fed back to all the input neurons through a crossbar network characterised by symmetric synaptic weights such that $w_{ij}=w_{ji}$ [Hopfield 1982, Hopfield 1984]. The feedback provides the synaptic inhibition. The symmetry of weights makes $\dot{E}=-\frac{dx_i}{dt}\left(\sum_j^n w_{ij}x_j+\theta_i\right)<0$ so that the energy function has a negative time gradient and its time evolution seeks the minima on the energy surface. Within the basin of attraction ther system is asymptotically stable. Furthermore, symmetry guarantees that all locally stable attractors are fixed points on the energy surface and that the network is globally asymptotically stable. The Hopfield net can store $n/_{2\log n}$ arbitrary state vectors [Michel & Farrell 1990, Abu-Mostafa 1989, Abu-Mostafa & St Jacques 1985]. Lack of symmetry in the connection weights introduces complex oscillatory and chaotic behaviours in the energy trajectory with no guarantee of stability. However if the connection weights are not symmetric then memory capacity may be increased to 0.27n [Amari 1990]. Their limited memory capacity may be overcome using modular units interconnected in complex ways. The Hopfield net may use binary or continuous state neurons. The output function in a binary neuron is approximated by a Heaviside function. The binary model has a binary output of ± 1 according to whether the weighted sum of inputs exceeds the fixed threshold value. This type of neuron is the adaptive linear element (adaline) [Widrow & Winter 1988]. Adaline adjusts weights by minimising the mean squared error using the Widrow-Hoff delta algorithm. The continuous network neuron stores a real number so that the neuron's state changes are continuous and this is modelled through a sigmoid function. The continuous analogue neuron produces a "fuzzy" response for neurons compared with the on/off response of the binary neuron. It appears that biological neurons are not in fact binary but are continuous and capable of synchronous switching due to their resistive and capacitance properties generating RC charging time delays.

Tank & Hopfield (1987) have tackled the problem of recognising features in time dependent input signals to a neural network by using sets of delays to focus on future sequences of inputs. Regularity often occurs in temporal input sequences of data, so it is necessary to store information over time in order to recognise time-dependent processes. Delay filters exhibit strong output during a short period at the end of the sequence and act as sequence detectors. This may be interpreted as a maximum likelihood (Bayesian) choice in that delays have continuous probability amplitude represented by minima in a spacetime energy landscape such that depth is a measure of evidence that a sequence was presented to the network. The energy surface channels the network trajectory where sufficient information has been presented in the past towards the correct solutions. To introduce dependence on time, activation state may be defined by its rate of change $\dot{a}=-\alpha a$ where α=activation decay rate. Equilibrium is reached when $\dot{a}=0$.

Dynamic recurrent neural nets may be represented by a set of differential equations:

$\tau_i \frac{dy_i}{dt} = -y_i + \sum_{j=1}^{n} w_{ji}\sigma_j(y_j) + I_i$ where τ_i=time constant

y_i=activation of node I
σ_i=sigmoid function=$\frac{1}{(1+e^{(\theta_j-\xi)})}$
θ_j=threshold
I_j=environmental inputs

BOLTZMANN MACHINE

The Boltzmann machine is a generalised variant of the Hopfield net which includes a hidden layer of units whereby the unit states are updated according the stochastic rules to avoid trapping in local metastable minimum configurations by adding thermal noise. A temperature parameter T is used in a probabilistic version of the sigmoid function so that the input and output vectors occur together with a given frequency. The probability that unit j adopts state 1 rather than state 0 is given by: $p_j = \frac{1}{1+e^{-\delta E_i/T}}$ where $\delta E_i = x_i w_{ij} = j^{th}$ unit input and T=temperature scaling factor. If the net input and noise exceeds the neuron threshold, it fires. Weights increase if the probability of activity of a neuron in response to stimulation is greater than the probability of activity of a neuron in the absence of stimulation. Control parameter T follows a simulated annealling schedule that allows the realisation of global optimum. The network will reach "thermal" equilibrium and at thermal equilibrium, the probability of the network being in any given state obeys a Boltzmann distribution: $\frac{p_i}{p_j} = e^{-(E_i-E_j)/T}$

At high temperature, the network approaches equilibrium rapidly (p_i=0.5) but high and low energy states are almost equally probable (high noise level). At low temperatures, the network approaches equilibrium more slowly (at T=0, p_i=1) but low energy states (low noise level) become much more probable. Simulated annealing is a search technique that escapes local minima. It starts at high temperature which is reduced gradually so the system reaches steady state at each temperature increment to find low energy states with high probability. Rapid quenching from high to low temperatures would lead to metastable states only. The learning cycle has two phases: positive and negative followed by weight adjustment. During the positive phase, the network is cycled through all the required input-output vector pairs, each being clamped into the input and output units. The whole network is then annealled from high temperature down to thermal equilibrium at temperature T=1. Each connection is then increased by $< w_i w_j >^+$. After all the input-output pairs have been presented, the negative phase is almost identical. The network is then run with the inputs clamped but without clamping the output units. The outputs are allowed to settle and each connection weight is measured $<w_i w_j>^-$. Each weight is updated by an amount in proportion to the difference between the weights between the two cycles: $\delta w_{ij} = \varepsilon[< w_i w_j >^+ - < w_i w_j >^-]$. If ε is small, a steepest gradient descent to reduce the difference in behaviour between the actual and desired cycles is performed to ensure that the outputs during the positive and negative phases coincide. The cross-entropy between the desired conditional probability distribution and actual conditional probability distribution of the output units is minimised. It is an unsupervised learning mechanism in depending only on correlation between pairs of units creating a distributed representation of those correlations. It is slower than backpropagation due to the time required to reach equilibrium but dedicated VLSI hardware reduces this.

SELF-ORGANISING NETWORKS

Self-organising neural networks which are competitive (unsupervised) learning have also been applied to adaptive pattern recognition. Such competitive learning is less efficient than supervised learning and is used to grade responses. Reinforcement learning occurs when goal directed performance is systematically changed by virtue of a series of punishment/reward responses. This ebetween learning about interactions concerning cause-and-effect relations betwen the system and the environment. A performance index can indicate the type of reinforcement to enhance response online. Inefficiency necessitates modular approaches to cope with power scaling with problem size. Local interconnection should be high with fewer interconnections between modules. Competitive learning is an unsupervised mechanism that divides a set of input vectors into a number of disjoint categories on the basis of their similarity. Hence each input neuron is dedicated to a particular feature. There is some neurological evidence for separate retinal cha–nels which are sensitive to intensity variations within specific ranges - specific neuronal feature detectors for contrastin– edges and lines do exist in the retina. There are two layers F1 and F2 - the output units represent confidence measures. Input vector to F1 represents STM trace which trains adaptive weights of layer F2 as LTM traces. Level F2 is the competitive network in that the nodes compete to become active and the node with the largest total input wins (winner take all). Credit is assigned to local divisions according to how it correlates to global reinforcement signal. The winning node adds a proportion of the input vector to its weight reducing the error through steepest descent. This is iterative and the node becomes increasingly sensitive to the specific input vector only, ie. it classifies the input pattern. Input patterns may be classified into mutually exclusive recognition categories through information compression through dimensionality reduction. The learning process generates the best distribution of LTM traces consistent with the inputs. Competitive learning can produce topographic maps. The hidden units have a spatial structure so that adjacent units respond to similar input patterns. It essentially perform dimensionality reduction so that redundant degrees of freedom are removed from the input vector. Competitive learning networks are essentially a form of self-supervised backpropagation networks using winner-take-all strategy instead of the normal non-linear input-output function. Error derivatives are simple to compute from the winner-take-all stategy. For restricted environments, competitive learning networks provide an efficient unsupervised learning mechanism by adapting self-organising techniques. Competitive learning networks are essentially pattern classifiers which classify on the basis of similarity using a winner-take-all strategy in the output layer. Such networks can generate sensory-motor topographic maps as learned correlations for adaptive coordinations. The variants include ART, neocognitron, self-organising maps and Darwin networks. The neocognitron has been used for vision processing and visual pattern recognition [Fukushima et al 1983]. It is a multilayer neural network with a hierarchical structure comprising a cascaded connection of many layers of cells. The stimulus pattern is given to the photoreceptor input layer and it is processed at each layer of the network. Each cell responds only to a specific stimulus feature acquired by learning. Feature sensitive detectors are known to exist in the brain which are specifically tuned to specific features. The cascading effect allows cells to group their responses into successively large subsets, ie. classification into categories. Cells at deeper layers have a tendency to respond selectively to more complex higher order features and has a larger receptive field with less sensitivity to image shifts and distortions. The final layer comprises of a single neuron whose receptive field is the entire image. Through the synapses between the cells, the network can learn. The neocognitron's recognition capabilities are robust to considerable distortion.

The self-organising map has only one layer of neurons each connected to the inputs. A neighbourhood is defined for each neuron, the size depending on the application. Coding is localised so that each neuron represents a particular class of inputs. During learning, neurons approximate the probability density function of the inputs. Learning projects the n-dimensional space of the training data on m-dimensional space of the SOM (typically, m=2). Competition occurs between all neurons. Kohonen map is an unsupervised learning neural network which provides categorisation capability that may be exploited for learning sensory-motor behaviours. It can be used by mobile robots to learn motor stimuli associated with a particular location such as timing between maneouvres. Cog uses the Kohonen net to learn its orientation behaviours from multimodal sensory data such as visual, auditory and tactile information. Connectionism offers a unified representation scheme for knowledge representation, perception and action, learning and problem solving. Neural networks may act as associative content-addressible memory and can generalise and learn [Pfeifer et al 1989]. They offer a framework for matching perception to action through sensorimotor systems. They are particularly suited to noisy data. Kohonen (1990) showed that hierarchical sets of ANNs can exhibit self-organisation and discover semantic relationships in sentences. The topological self-organising map has an input layer fully connected to a map layer and represents an unsupervised method of categorisation of input patterns. In the map layer, there are lateral connections – close neighbours are connected by excitatory links while further neighbours are connected by inhibitory links, and the furthest nodes are connected by neutral links. Patterns presented to the input layer allow the networks to categorise the input patterns. The process is one of pattern classification where each neuron becomes specifically tuned to different signal patterns (such feature-sensitive neurons exist in the brain) so that patterns are grouped into subsets each of which corresponds to a discrete class – effectively a decision procedure. Input signal patterns correspond to spatial coordinations of cells in the network. The self-organising map pattern classifier extracts abstract information from the input signals and represent it as 2D network locations.

The Kohonen self-organising network contains a single layer with many connections with weights adjusted to group neurons of topologically ordered fields which compete in a winner-take-all fashion. The basic principle is to map the input space R^n onto a two dimensional rectangular array of nodes where each node is characterised by a reference vector $w_i \in R^n$ associated with it. The input patterns (feature vectors) are shown to all neurons simultaneously but each neuron outputs only one value (feature selection). The inputs $w_i \in R^n$ are compared with w_i and the closest vector in terms of Euclidean distance is the winner. A winner-takes-all strategy implements competitive learning so that the neuron with the largest response is chosen. The distance between the input and the net of the neuron is given by:

$$d = \sqrt{\sum (x_i - w_{ij})^2}$$

Given that the Kohonen net attempts to match the input to its weight, the neuron with the shortest distance is selected and determines the weight change:

$\Delta w_{ij} = k(x_i - w_{ij})$ where k=learning coefficient

All neurons in the neighbourhood around the shortest distance neuron must have their weights adjusted. After training, the output space defines neighbourhoods of similar inputs. The network finds its own energy minima through computation of the equilibrium states of the network.

Radial basis function networks utilise localised receptive fields in the form of an input layer with current input values, a hidden layer representing the number of classes in the input space, and an output layer which integrates the degree of membership computed by the hidden layer. This computation is computed on the basis of the cluster centre μ and width σ. The hidden neuron representing the cluster provides the highest output when the input it receives is close to its centre.

The output is determined by the neuron’s transfer function and the Euclidean distance. The output of the network is given by:

$$y_j = f(x) = g\left(\left(\sum_{i=1}^{n} w_{ij} r_i(x)\right)\right)$$ where g=transfer function (typically identity function)

w_{ij}=weight between output neuron j and cluster I
$r_i(x)$=membership value for cluster I
$= e^{-\left(\frac{|x-\mu_i|}{\sigma_i}\right)^2}$
μ_i=centre of cluster
σ_i=width of cluster

Output neuron output with time delay d in hidden layer is given by:

$$y_j = g\left(\left(\sum_{i+1}^{n}\sum_{k=0}^{d} w_{ijk} r_i(x(t-k))\right)\right)$$ where d=number of time steps

RBF networks are universal approximators and the number of clusters, their centres and widths must be determined.

One major difficulty with ANNs is the plasticity-stability dilemma. The learning phase precedes the recognition phase and learning is characterised by plasticity described by nmemonic equations while recognition requires stability and is described by a neuronic equation [Caianello 1961]. This separation of learning and operation is not biologically realistic. The mnemonic equations describe learning and have much slower timescales than the mnemonic equations describing operational performance. The connection weights which are modified during learning are effectively frozen over the short operational periods. The principle of minimal disturbance states that adaptation should be to reduce the output error for current training patterns with minimum disturbance to responses all ready learned. Plasticity allows prior learning to be superceded by more recent learning of perhaps irrelevant events. To combat this, adaptive resonance theory (ART) has been proposed which ha its basis in inference patterns and reverbatory circuits in ANNs [Grossberg 1980, Carpenter & Grossberg 1988]. Adaptive resonance theory (ART) learns stimulus patterns without an external teacher. The attentional system learns top-down expectancies which attempts to match to bottom-up input patterns. Mismatches activate an orienting system to reduce the mismatch by recoding. An input pattern activates F1 which in turn filters and activates the higher level F2 (the hypothesis) node. Natural modes of resonance of a network may be tuned to certain inputs. For multiple inputs, all that is required is that a sufficient portion of the characteristic pattern to which the subsystem is tuned is exhibited. F2 passes the top-down expectation as a template to F1 to match the bottom-up input pattern in a feedback pathway. Such reciprocal feedback exists in the thalamocortical network of the brain. This feedback provides stability. If the match is bad, a reset is triggered to F2 to deactivate the winner node and F2 chooses another node in F2. This provides arousal to novel stimuli through an arousal mechanism (reticular formation). This process is so fast that learning is adiabatic as the LTM trace is effectively frozen with respect to the STM trace and the inhibitory reset wave isolates STM from LTM. The arousal process is complimentary in that it directs attention to acquiring new information through search to attempt to correct the error. The top-down expectation focusses attention on the bottom-up information to protect previous knowledge. Concensus between bottom-up and top-down information represents attentional focus in that the two way signal flow mutually reinforce each other through feedback into resonance creating amplification and prolongation. Only then in the resonant state will LTM of the F2 layer learn, ie. when sufficient similarity exists between old and new information. Competitive interaction between cells automattically retrieve their sensitivity in a form of noise suppression and different cells respond to different inputs. Recurrent dynamics provides the means for feedback enhancement between STM and LTM until the two processes equilibriate. There is a critical period before which STM encoding into LTM cannot occur. The reset wave ensures that LTM is stabilised to erosion by environmental fluctuations. If matching does occur, resonance ensures that the STM trace persists allowing it to be sampled for storage into the LTM. The overall pattern of mutually consistent resonance, activity that is consistent across all levels of representation. Resonance may be a general property of neural circuit interactions in the brain, eg. in binocular vision. It provides a means for grouping neural circuits into higher neural circuits in a hierarchical organisation of coding mechanisms to cope with real-time operation. Such assemblages of partially redundant loosely coupled subsystems capable of autonomous resonant excitations will be robust to structural damage. Many different nodes of resonance can occur across different ranges of perceptual inputs with the resonance hierarchy being nested rather than sequential as in the neural circuit hierarchy. Hence, this provides a means for both horizontal and vertical hierarchies of representational coding. Resonance is thus an emergent property of sets of neural networks. The resonant nodes bear the useful information as the units of cognitive coding. Gestalt switching may be a result of alternate resonances from the same image. Shephard (1984) has suggested that resonance can occur through spontaneous internal random excitation without external information from the senses producing phenomena such as hallucinations and dreams. A range of phenomena are characterised by different degrees of expectations (top-down)/perceptual (bottom-up) processing. Unstructured stimuli yield only meaningless experiences. At the other end of the scale, imagination and dreaming involve only the highest conceptual resonances. Between the two extremes lie perception and cognition. Biological evolution and learning requires an organism to be tuned to resonate to incoming patterns that correspond to important parameters that are significant for it.

REINFORCEMENT LEARNING

The human brain includes multiple memory systems. Remembering refers to recognition during recall of events (episodic memory residing in frontal lobes) which is to be differentiated from knowing which refers to recognition without such recollection (semantic memory residing in the medial temporal lobes) [Knowlton 1998]. Episodic memory can only exist if semantic memory for the episode is also present. Remembering is knowing with an additional component – the episode. Early learning is constrained by two fundamental in-built concepts – continuity (object move in connected pathways) and solidity (no two objects coincide with each in the same location) – whereas gravity and inertia are learned through perceptual-motor actions on the world [Spelke et al 1992].

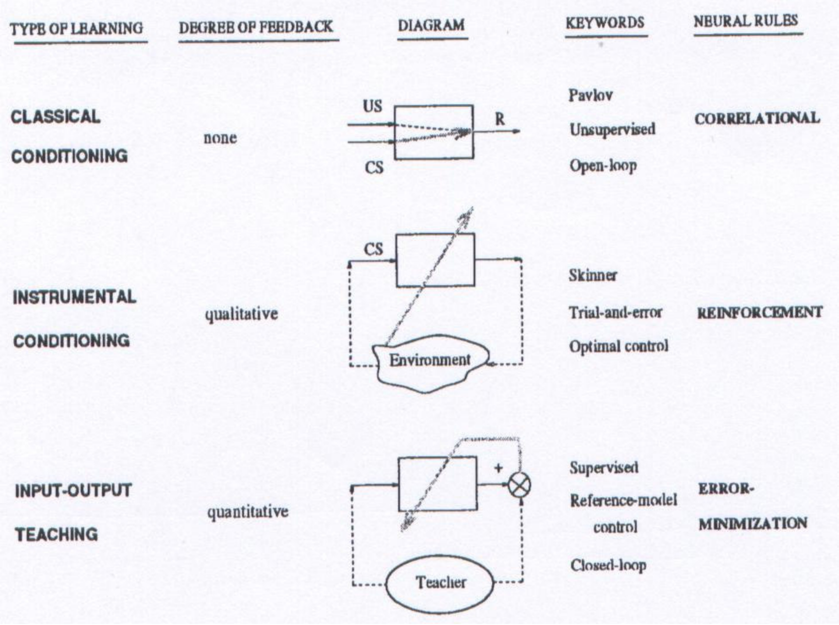


Fig A-1 Learning paradigms in neural networks [from Torras 1995]

Replanning requires reinforcement learning of which Q learning is the best known example [Watkins & Dayan 1992]. Reinforcement learning is based on an agent and its interaction with the environment. The environment is the source of rewards/punishments. Reinforcement learning involves a control policy which defines actions to be performed for a given state: f(x): S → A. This policy must maximise the accumulated reward over time, typically discounted according to time such that return is given by:

$$R(t) = \sum_{i=1}^{\infty} \delta^i r_{t+i}$$ where δ=discount rate, $0 \le \delta \le 1$

r_{t+i}=reward at time t+i

Rewards far in the future are less rewarding than earlier rewards. Actions are choices made by the agent, the states are the basis for that choice while rewards are the basis for evaluating the choices. The agent selects its actions on the basis of environmental state – these environmental state signals are Markov processes which include current sensory data. The Markov property is that the state signal includes all information about the complete sequence history relevant to the future behaviour, ie. the system is path independent and does not rely on the system's history. The next state may be predicted from the current state and action. An agent tries an action at a particular state and evaluates is consequences in terms of immediate reward or penalty it receives and its estimate of the value of the state to which it finds itself in. By trying all actions in all states, it learns which ones are best according to a time-discounted reward. The agent implements a mapping from the states to the probability of selecting a possible action by maximising its expected reward – this is the agent's policy. Q learning is a model-free incremental method of reinforcement learning by successively improving its evaluations of its actions. The Q learning algorithm estimates the optimal action value function Q(s,a) which maximises the total discounted expected reward through trial and error interactions with the environment where s=state, a=action. During learning, the agent chooses action a from state s using policy Q. Q learning is a form of reinforcement learning whereby an action function Q(x,a) evaluates the utility of performing action a in state x, ie. the expected reward. The idea is to find the control policy f(x) of actions that maximises Q(x,a). At each iteration, Q-values are updated as:

$Q_{t+1}(x,a) = (1-\eta)Q_t(x,a) + \eta\big(r + \delta U(x)\big)$ where $U(x) = \max Q_t(x,a)$

Reinforcement learning involves mapping between perceptions and actions defined by a policy which attempts to maximise performance quantified by a reward. Such reinforcement algorithms are slow to learn and require extensive repeats to generate trial-and-error responses before finding advantageous ones. During the nth episode, the agent:

(i) observes its current state s_n
(ii) selects and perform action a_n
(iii) observes subsequent state s'
(iv) receives immediate payoff r_n
(v) adjusts its Q_{n-1} values according to:

$Q_n(s,a) \leftarrow (1-\alpha_n)Q_{n-1}(s,a) + \alpha_n\big(r_n + \gamma \max_{a'} Q_{n-1}(s',a')\big)$ where α=learning rate ($0<\alpha<1$)

γ=discount rate ($0<\gamma<1$)

For finite Markov processes, Q learning is optimal – this requires analysis of the sensory properties of the robot to determine if the Markov assumption holds, ie. no perceptual aliasing. However, Q(λ) is more effective for robot behaviour learning than one-step Q-learning – Q(λ) combines Q learning with temporal difference method [Wyatt et al 1998].

Reinforcement learning may be incorporated into neural networks by [Scheier & Lambrinos 1995]:

$\Delta w_j = v(t)\big(\eta Q a_j(t) - \varepsilon\big((Q + a_j(t)\big)w_j(t)\big)$ where Q=Q-factor

v(t)=reinforcement value

η,ε=learning/decay parameter

Reinforcement learning generates a mapping between situations and actions by maximising a performance measure of the desired behaviour. In particular, it is a sequential process through proceeds through trial and error. The agent's goal is o learn a policy $\pi : s \rightarrow a$ which maps between states and actions. Q learning stores the expected reinforcement value associated with each situation-action pair in a look-up table. The optimal policy generates the highest cumulative reward:

$V^{\pi}(s(t)) = \sum_{i=0}^{\infty} \gamma^i r(t+1)$ where γ=discount factor

States are typically defined as sensor values – hence the state of the environment is only partially observable. The temporal difference learning algorithm uses observations of prediction differences from consecutive states to update value predictions:

$V(s_t) = V(s_t) + \alpha[V(s_{t+1}) - V(s_t) + r_t]$ where α=learning rate

r_t=current reward

The difference in prediction from consecutive states is used as a measure of prediction error. The temporal difference algorithm adjusts Q-values after each decision.

For robotics, the reinforcement signal may be defined as:

RF = +1 if obstacle avoidance
-1 if collision occurs
0 otherwise

Q learning can be improved through the use of an artificial neural network such as the self-organising map which improves the quality of generalisation and memory requirements [Touzet 1997]. The inputs were the situation, action and Q values. Learning associated each neuron of the SOM with situation-action pair plus its Q value. The number of neurons equals the number of stored associations. The SOM by virtue of its neighbourhood property can generalise across similar situation-action pairs. The learning algorithm updates the Q value, situation and action weights. Reinforcement learning using an associative reward penalty neural network has been applied to a six-legged robot whereby the reinforcement signal is generated by a critic from the environment and from the effects of the actions made - the critic takes the form of basic behaviours [Johannet & Sarda 1999].

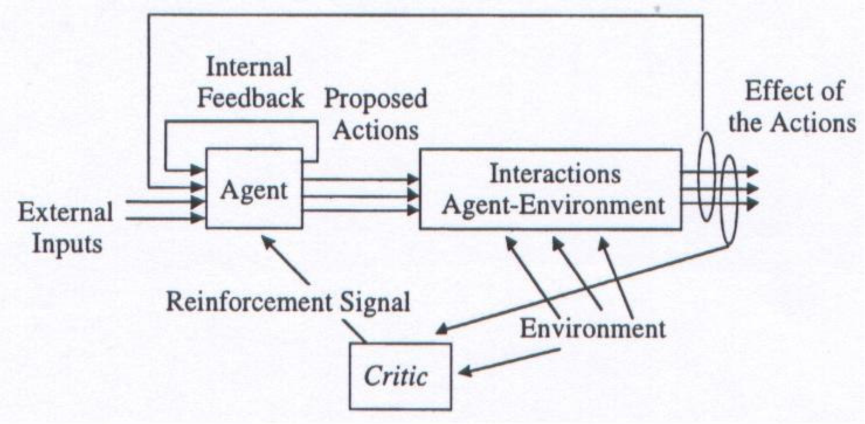


Fig A-2 Learning by reinforcement [from Johannet & Sarda 1999]

Evolutionary algorithms have similarly been applied to reinforcement learning problems, eg. EARL [Moriarty et al 1999]. Policies are represented as neural nets where the genetic algorithm is used weight optimisation process, eg. SANE or policies may be represented as distributed populations of rule-based classifier systems, eg. ALECSYS and SAMUEL. The chief advantage of using genetic algorithms is that maintaining a diverse population with a higher mutation rate, non-stationary environments can be tracked if they change slowly enough. Their chief disadvantage is a loss of long-term memory due to mutation if rare states arise. SAMUEL uses a single chromosome, high level rule-based representation for policies which allows incorporation of existing symbolic knowledge such as from case-based learning for the control and navigation of a mobile robot. ALECSYS is a distributed rule-based classifier system which was used to develop behavioural rules for mobile robot behaviour and navigation. SANE used genetic algorithms to generate weighted connections of a neural network to represent policies for the control of a robot arm.

ASSOCIATIVE LEARNING

When a conditioned stimulus (CS) is followed by an unconditioned stimulus (US), a CS-US association is formed. The CS through this S-S association predicts the US. In classical conditioning, CS-US associations are represented by the synaptic connections between the CS neural population and the US neural population, the latter controlling the generation of CR. As learning proceeds through the delta rule, CS comes to generate the CR. In classical conditioning, the timing relations between presynaptic and postsynaptic signals is important such that plasticity depends on the firing rate. The dorsal premotor cortex, basal ganglia and hippocampus play roles in learning arbitrary visuomotor mappings between antecedent and consequent [Wise & Murray 2000]. The hippocampus participates in classical conditioning which may be modelled by a multilayer neural network with a layer of hidden units trained by backprogation [Schmajuk & DiCarlo 1992].

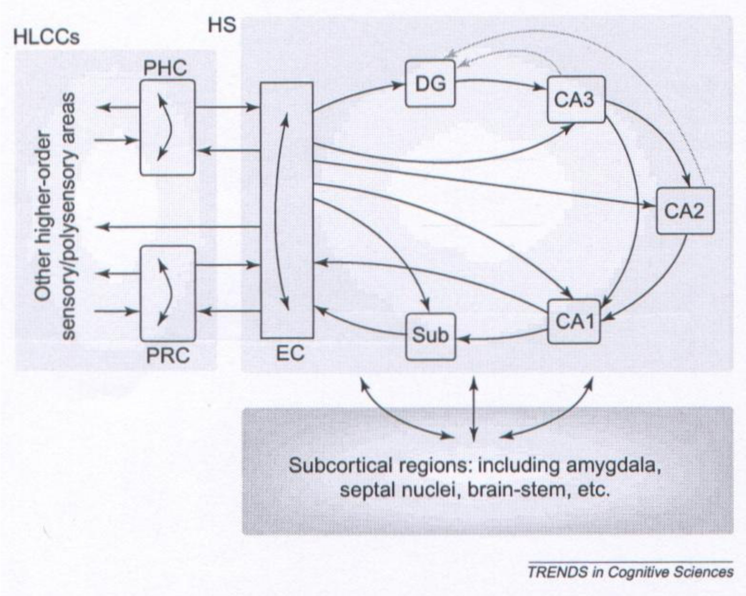


Fig A-3 Interconnections of the hippocampal system and cortical/subcortical areas – HS includes entorhinal cortex, dentate gyrus, Ammon's horn (which itself includes areas CA1, CA2 and CA3), EC is major portal between HS and cortex [from Shastri 2002]

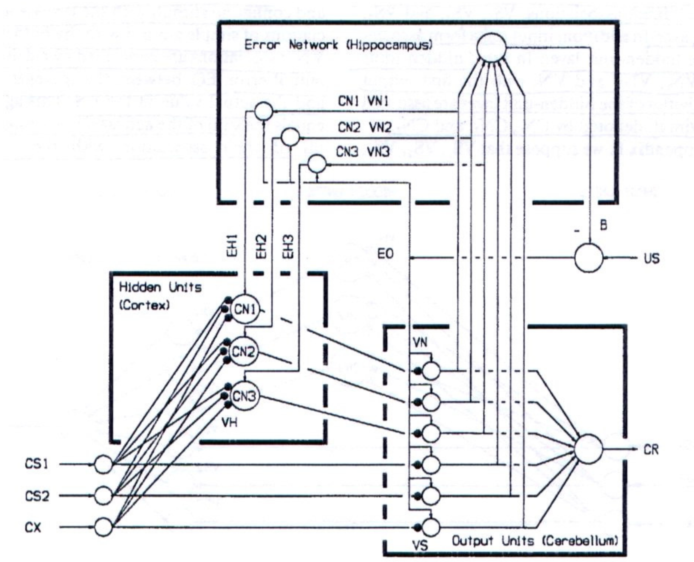


Fig A-4 Schmajuk-DiCarlo model: CS=conditioned stimulus, CN=configural stimulus, US=unconditioned stimulus, VS=CS-US association, VN=CN-US associations, VH=CS-CN associations, B=aggregrate prediction, CR=condiorioned response, EH=error signal for hidden units, EO=error signal for output units [from Schmujak & DiCarlo et al 1992]

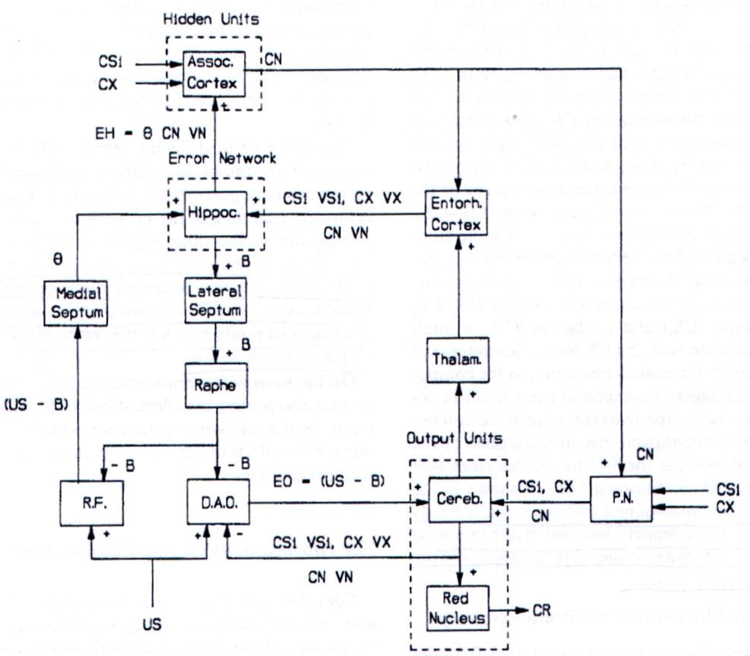


Fig A-5 Cortical, hippocampal and cerebellar interconnections: CS=conditioned stimulus, CX=context, US=unconditioned stimulus, CN=conditioned stimulus, VS=CS-US associations, VX=context-US associations, VN=CN-US associations, CR=conditioned response, B=aggregate prediction, EO=US-B output error, θ=theta rhythm, VN=hidden unit error, RF=reticular formation, DAO=dorsal accessory olive, PN=pontine nucleus [from Schmujak & DiCarlo 1992]

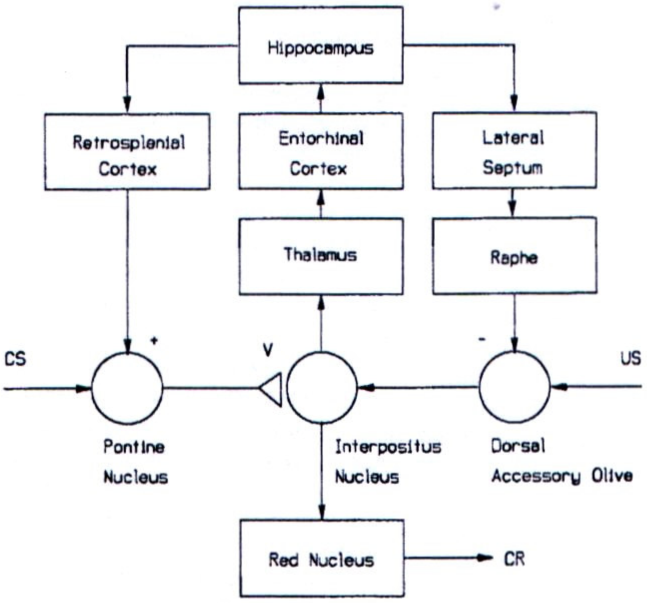


Fig A-6 Hippocampal regulation of CS and US inputs to cerebellar locus of learning [from Schmujak & DiCarlo 1992]

Pyramidal activity in CA3 and CA1 of the hippocampus is correlated with CR or CS. Cerebellum is critical for conditioning – the pontine nucleui conveys CS information while the dorsal accessory olive carries US information. CR activity originates from the cerebellar lobule VI and interpositus nuclei to the contralateral red nucleus. There are hippocampal projections to the pontine nucleus which modulates mossy fibre activity to the cerebellar cortex and interpositus nuclei. Thus, hippocampal output might regulate CS of the pontine nucleus and US of the dorsal accessory olive inputs to the cerebellum. The Schumajuk-DiCarlo model models a classical conditioning network with an error network such that outputs represent cerebellar circuits while hidden units represent cortical circuits. The hippocampus is modelled by the error network. Klopf (1988) suggested modifications to the Hebbian rule to implement classical conditioning through unsupervised learning by correlating changes in earlier pre- and later post-synaptic activity to generate synaptic weight changes in proportion to current synaptic efficacy during learning. This is the drive reinforcement model of neural function which treats drives as neural signal levels and reinforcers as changes in neural signal levels to overcome some of the deficiencies of the Rescorla-Wagner and Sutton-Barto models.

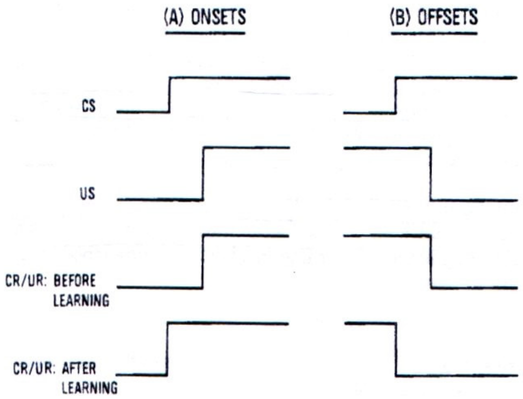


Fig A-7 Drive-reinforcement learning mechanism alters onset and offset of pulse trains for single neuron: CS is followed by US (presynaptic); CR and UR before and after learning (postsynaptic); neuron learns to anticipate UR by learning to fire earlier or stop firing earlier [from Klopf 1988]

A computational model of the nervous system during classical and instrumental conditioning has been developed which operates in real time closed loop goal seeking environments and learns to avoid punishment and seeks rewards [Klopf et al 1993]. The core was an associative learning control system which implemented classical conditioning (open loop) and instrumental conditioning (closed loop).

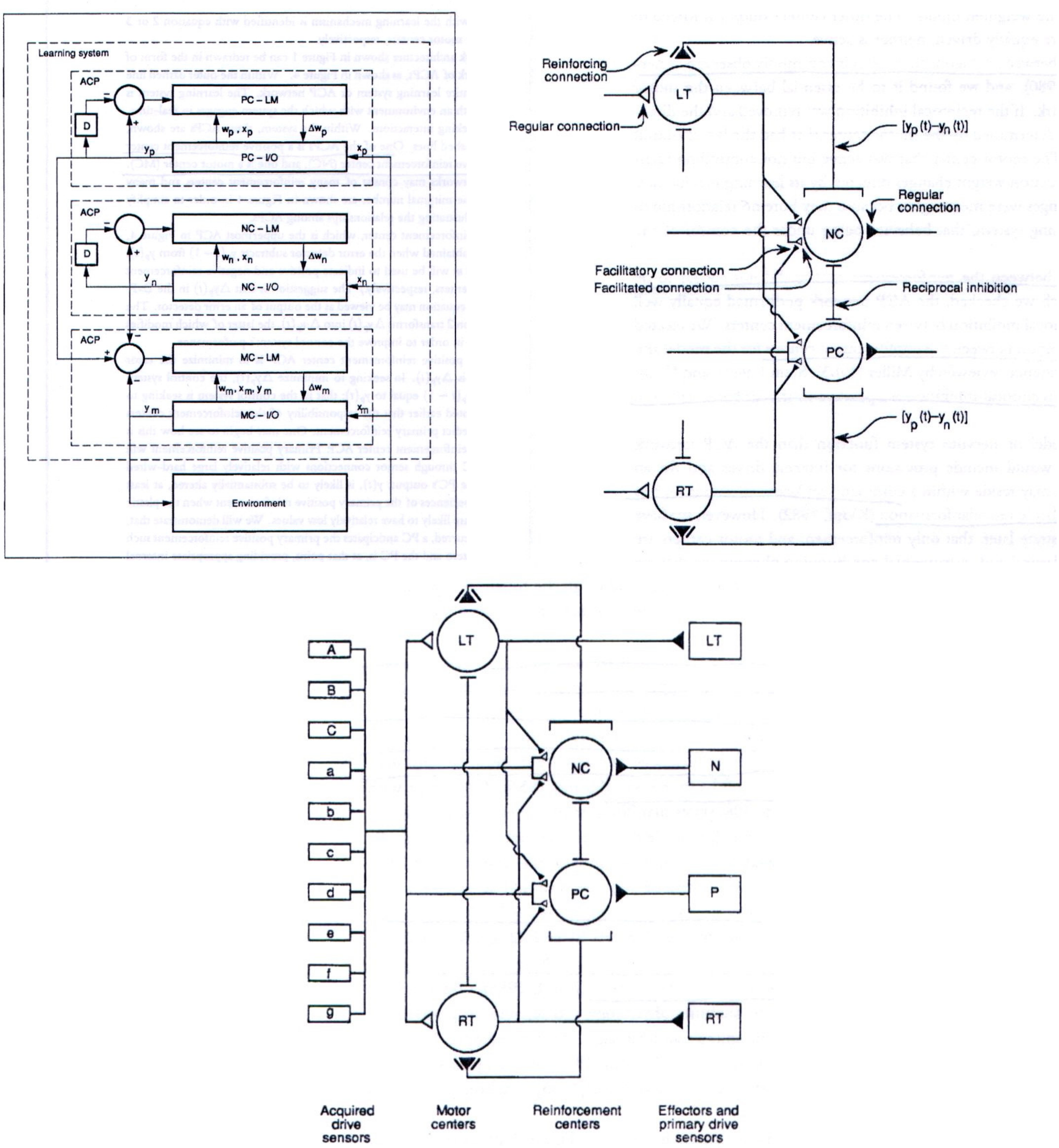


Fig A-8 (a) Association control processor network architecture; (b) connection types in ACP; (c) ACP interconnection pattern for sensors, motor centres, reinforcement centres and effectors [from Klopf et al 1993]

Animals learn instrumental responses by firstly acquiring emotional (reinforcement) responses and then this is used to guide learning of the appropriate motor behaviour. Reinforcement from the limbic and hippocampal system thus provides the predictive signal for motor learning of appropriate behaviour. Positive reinforcement (reward or pleasure) promotes approach behaviour while negative reinforcement (punishment or pain) promotes avoidance behaviour. Reinforcement centres are reciprocally inhibited between antagonistic actions. Primary drive sensors have hard wired connections (US) while acquired drive sensors have plastic connections (CS) to the association centres. Learning involves modifying the weights of the acquired drive sensor connections (CS). The drive reinforcement learning mechanism correlates earlier changes in input signals with later changes in output signals and changing the connection weights to model these correlations through the i/o equation:

$$y(t) = L\left(\sum_{i=1}^{m} w_i(t)x_i(t)\right) \quad \text{where } L(v) = 0 \text{ if } v<\theta$$

$= 1$ if $v>1$
$= v$ otherwise
$y(t)$ = output at time t
w_i (t) = connection weight (efficacy)
x_i (t) = amplitude
θ = threshold
m = number of input connections

This implementation of thresholding generates rapid convergence to the desired weights. The learning mechanism is given by:

$$\Delta w_i(t) = \Delta y(t)\sum_{j=1}^{\tau} \eta_j \mid w_i(t-j) \mid \left[\Delta x_i(t-j)\right]^{+} \quad \text{where } \Delta w_i(t) = w_i(t+1) - w_i(t)$$

$$\Delta y(t) = y(t) - y(t-1)$$

$$\Delta x_i(t-j) = x_i(t-j) - x_i(t-j-1)$$

$$[\Delta x_i(t-j)]^{+} = \max(\Delta x_i(t-j), 0)$$

Weight changes occur at t+1 as a function of pre-synaptic input at time t-j, post-synaptic output at time t, and current weight efficacy at time t-j. Each time step τ ~500 ms for optimal interstimulus learning. Such temporal contiguity between a CS and a US is fundamental to classical conditioning with CS providing a predictive value. Weighted inputs are defined as drives and weight changes in inputs are defined as reinforcers so that drive reinforcement promotes learning of excitatory and inhibitory processes depending on the reinforcement value. A variation which allows simultaneous UR and CS learning is the modify the input as: $\Delta y(t) = y(t) - y(t-1) + UR(t)$. Motor learning uses a different learning scheme:

$$\Delta w_i(t) = \eta[\mid w_i(t) \mid][\Delta x_i(t)]^{+}[y_p(t) - y_n(t) - y(t)][\text{sgn}[y(t)]]$$

$$\text{where } \eta = \eta_a + \left(\mid y_p(t) - y_n(t) \mid\right)\eta_b$$

η_a, η_b = learning rate constants
$y_p(t)$ = positive reinforcement centre output
$y_n(t)$ = negative reinforcement centre output
$y(t)$ = motor centre output
sgn[y(t)] = 1 if y(t) > 0
= 0 otherwise

The CS is followed by the US representing presynaptic signals with CS undergoing variable synaptic weight. The CR and UR before and after learning from CS-US pair presentations represent postsynaptic signals. This model correctly predicts the S-shaped learning curve of classical conditioning unlike the Rescorla-Wagner and temporal Sutton-Barto models. Instrumental conditioning (SR association) emerges from the classical conditioning (SS association) neural substrate.

FRACTAL & CELLULAR NETWORKS

Barto et al (1983) pointed out that biological neurons are in fact complex rather than simple processors that utilise complex biochemical cellular mechanisms. They proposed a two-neuron system of an associative search element (ASE) and an adaptive critic element (ACE) for control problems such as pole-balancing. In the course of learning, ASE constructs associations between input and output through reinforcement feedback. ACE constructs more an informative evaluation function than reinforcement feedback. This evaluation function assesses the consequences of actions. ASE discovers what responses lead to improvements in performance by trial and error. Actions that lead to improved performance when taken in the presence of certain input signals between the source of associative input/output mappings. ACE performs the function of a critic based on relative measurement of consequences of actions. This adaptive evaluation function must reduce the uncertainty under which the ASE must learn. In effect, ACE supplies internal reinforcement to the ASE throughout the trials. The ASE element has a reinforcement input pathway and n non-reinforcement input pathways $x_1(t),\ldots x_n(t)$ and a single output pathways y(t):

$y(t) = f\left[\sum_{i=1}^{n} w_i(t)x_i(t) + n(t)\right]$ where n(t)=noise, f is a sigmoid function.

Each neuron's present pathway i has an associated weight $w_i(t)$. The weight changes are given by: $w_i(t+1) = w_i(t) + \eta r(t)e_i(t)$ where r=reinforcement signal and e=eligibility

Eligibility allows a trace of the product $y(t)x_i(t)$ which persists after conditions cease to apply and decays exponentially: $e_i(t+1) = \delta e_i(t) + (1-\delta)y(t)x_i(t)$ where δ=trace decat rate. Reinforcement may be rewarding (positive) or punishing (negative). The ACE receives the externally supplied reinforcement signal which it uses to determine how to generate an improved reinforcement signal for the ASE based on the environment. The ACE has a reinforcement inout pathway, n non-reinforcemenI input pathways and a single output pathway. Each reinforcement pathway i has a weight $v_i(t)$. The output is the improved reinforcement signal $\hat{r}$. Prediction p(t) of the reinforcement signal is a function of the input vector x(t):

$$p(t) = \sum_{i=1}^{n} v_i(t)x_i(t)$$

The weight update rule so that p(t) converges to the prediction is given by:

$v_i(t+1) = v_i(t) + \eta[r(t) + \gamma p(t-1)]\bar{x}_i(t)$ where η=learning rate

0<γ<1=discount "forgetting" factor

$\bar{x}_i$ =trace of $x_i(t)$

$$\bar{x}_i(t+1) = \lambda\bar{x}_i(t) + (1-\lambda)x_i(t)$$

From this improved reinforcement: $\hat{r}(t) = r(t) + \gamma p(t) - p(t-1)$

The reinforcement signal $\hat{r}(t)$ sent to ASE define increases in reinforcement prediction as rearding events and decreases as punishment events. This scheme is much more complex than previously considered learning systems and ACE effectively models classical conditioning consistent with the Rescorla-Wagner model of classical conditioning. A failure signal v to US, the signals x_i correspond to potentials CS's and the prediction p corresponds to components of CR.

Baram (1989) proposed fractal ANN's to overcome the capacity limitations of the Hopfield net. Such a network comprises subnetworks corresponding to different layers with the same geometric form but different sizes. Subpatterns are stored in such subnetworks. Interlayer connectivity is such that each neuron in a given layer is included as the subnetworks of lower layers. They can thus create a hierarchy of subnetwork layers. Each neuron is directly connected to the neurons in the two subnetworks. This is a fractal form due to the high degree of self-similarity and requires fewer connections than a fully connected network. Only a few subpatterns can be stored in each subnetwork but for the whole network, the storage capacity is very large as two orthogonal patterns can be stored in a fully connected subnetwork of three networks.

Chua & Young (1988) proposed a new "cellular" neural network similar to cellular automata networks as generalised Hopfield nets. It comprised a large scale nonlinear analogue circuit of N-dimensional array of cells which processed signals in real-time. The cellular array may be planar (rectangular, triangular or hexagonal) or 3D finite array such as a sequence of 2D arrays. Each cell of the network circuit comprised of a linear capacitor, a nonlinear voltage-controlled current source with a sigmoid characteristic, and some linear resistive elements. Each cell could be realised by an operational amplifier. Each cell communicated directly only with its nearest neighbour, and may interact only with other cells through propagation effects, ie. connections are local. Cellular automata are Turing equivalent. The energy-like Lyapunov function E(t) with $\overset{\lim}{\underset{t\to\infty}{E(t)}}$ =constant defined its stability with $\frac{dE}{dt} \leq 0$. Each cell of the cellular neural network settled to a stable equilibrium point after transients had decayed. The transients represented the trajectory between equilibrium points and all trajectories were characterised by the basin of attraction forcing them to converge to the equilibrium limit points. The propagation effects of local interactions provided some global properties despite the localised interconnectivity. They were demonstrated as filters in highly parallel image processing tasks.

COMPACT ENCODING

Localist dynamics are commonly modelled by winner-takes-all competitive neural networks. This winner-takes-all strategy underlies self-organisation into neural maps in which specific neural groups respond to a distinct sensory input. Maps are topographically ordered projections from a receptive area to a specific brain area, eg. the somatotopic homunculus in the sensorimotor cortex, the directional hearing map in the owl midbrain, and the target range map in the bat's auditory cortex. A typical cortical map for a single feature is ~5mm wide. The self-organising process may be realised by a set of neurons in a regular planar array where each neuron represents a model as a set of numerical values denoting synaptic efficiency. [Kohonen & Hari 1999]. Competition between neurons occurs when stimulated by a common input and the neurons whose parameters are closest to the input is stimulated maximally. The correlation between input x and model w defines the degree of match: $w_{i1}x_1 + \ldots + w_{in}x_n$. The winner has the highest correlation measure: $w_c.x = \max_i\{w_i.x\}$. Learning through self-organisation modifies values $w_i(t)$ to new higher values while the normalised vector length is preserved: $w_i = \sum_{j=1}^{n} \sqrt{w_{ij}^2}\big/_{j}$. This winner neuron suppresses the activity of neighbouring neurons through lateral inhibition. When neighbouring neurons are modified by learning to resemble the input, they also tend to become more similar. These neighbouring neurons acquire numerical values that relate to each other smoothly. Self-organisation involves modification of synaptic strengths in the winner's neighbourhood according to Hebb's law of the form: $w_{ij}(t+1) = w_{ij}(t) + \eta\alpha_i(t)x_j(t)$ where α=neural activity. A forgetting factor is included so that w_{ij} does not diverge: $w_{ij}(t+1) = w_{ij}(t) + \eta\alpha_i(t)x_j(t) - \beta(w_i(t).x(t))w_{ij}(t)$. This increases synaptic efficiency in proportion to the conjuction of presynaptic and postsynaptic activity in the neuron. Chemical messengers such as nitric oxide can modify neighbouring neurons. The winner-takes-all strategy can generate sparse representations and clustering. Symbolic written words may be converted into numerical input vector through arbitrary association with different random vectors, one for each word. Winner-takes-all stategy generally require slow learning and suffer from catastrophic forgetting. A number of approaches can alleviate these problems [Carpenter 2001]:

(i) replacement of traditional synaptic transmission rule of $T_{ij} = I_i w_{ij}$ by $T_{ij} = f(I_i w_{ij})$ where I_{ij}=presynaptic input, T_{ij}=postsynaptic signal

(ii) use cortical feedback loops

Neurons can be replaced by expert modules whereby linear summation output is replaced by a gating network which combines the expert module outputs [Intrator & Edelman 1997]. During training, the gating network learns to direct to each expert system to those patterns on which it performs best. The error used for training is affected by the amount of belief in each expert determined by the gating network – this can be achieved through Bayesian methods.

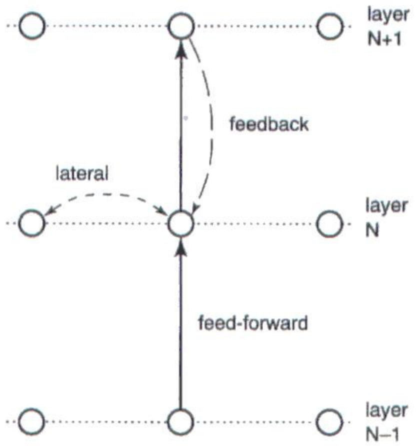


Fig A-9 Competitive learning via lateral inhibition in a feedforward network [from Intrator & Edelman 1997] – units in each layer are connected through excitatory connections to other layers while inhibitory links connect within each layer to implement competition between neurons

Artificial neural nets may be combined into sets of nets, each of which is designed as a general function approximator (ensemble or committee approach) to tackle the same problem (perhaps by varying initial weights, topology, learning scheme, training data, the latter being the most effective), or the problem may be decomposed into subtasks and solved using several modular specialist nets, each of which performs a different task (modular specialist approach) [Sharkey 1996a,b, Sharkey & Sharkey 1997]. The ensemble approach recombines the individual outputs while the modular approach allows the use of supervisory hierarchies. The modular approach includes mixtures-of-experts approaches where output is combined using a gating network. Combining outputs may be through weighted averaging, Dempster-Shafer belief methods, and Bayesian methods. The chief difficulty is that the effect of scaling to large sizes increases learning times exponentially. This may be partially overcome by partitioning networks into modular hierarchical distributed systems. Each module comprises of an upper bound of neurons and various modules operate independently. A large number of activated modules may then interact with each other in parallel. Neural learning provides the basis for the development of "mixtures of experts" neural modules of the brain that develop through maturation in early life [Jacobs 1999]. Neural selection involves different brain regions competing in the development of specialised neural modules for the performance of a given set of tasks. The learning process proceeds by neural selection where some plastic neural connections are stabilised while others are eliminated. The input pattern provides a bias that determines the nature of the processing for the task. There are two types of network – expert networks and a gating network. The expert networks compete to learn the input-output training patterns mediated by the gating network. The gating network has each expert network as its output, and the output y of the entire architecture is a linear combination of the expert networks outputs:

$y = \sum_{i=1}^{n} g_i y_i$ where g_i=gating network output of ith expert network

The expert network whose output most closely matches the target is the winner of the competition. Different expert networks are thus forced to learn different tasks. The gating network determines the extent to which each expert network's output contributes to the overall output of the complete architecture. The gating network acts as inhibitory connections between the expert networks so that the appropriate expert network can suppress the outputs of other expert networks. The strength of the inhibitory connections depend on the current input pattern, ie. the context. Functionally specialised neural modules develop by parcellation which regressively eliminates synaptic connections – columnar structures of the cortex probably form in this manner. Presynaptic neurons compete for a limited supply of molecules that are released by postsynaptic neurons. Those presynaptic neurons that acquire sufficient amounts of these molecules maintain their connection to the postsynaptic neuron. The amount of trophic factor available to the presynaptic neuron is increased by synchronous activity of the presynaptic and postsynaptic cells, ie. the competition for trophic factor is Hebbian such that the change in synaptic weight changes as: $\Delta s = (post \times pre) - decay$.

Learning in recurrent neural networks requires consideration of time dependency by using recurrent connections which transmit with time delays. Hence, neuron output is determined by:

$y_i^t = f\left(\sum_i w_{ij} x_j^t + \sum_k c_{ik} y_k^{t-1}\right)$ where c_{ik}=recurrent connections

The output is dependent on outputs from previous time step from neurons in the same layer. Extra input units connected to hidden units with feedforward connections that hold a copy of the activations of other units at the previous time step (memory). Elman's architecture has memory units with a copy of the values of hidden units at the previous time step. As hidden units encode their own previous states, the network can detect and reproduce long sequences in time. Jordan's architecture has memory units with a copy of the values of output units at the previous time step combined with weighted activation of memory unit itself at previous time step. More complex time dependent dynamics can be generated with continuous time recurrent neural networks:

$\tau_i \frac{\partial a_i}{\partial t} = -a_i + \sum_j w_{ij} f(a_j) + I_i$ where τ_i=time constant

a_j=mean activation state
$f(a_i) = \frac{1}{1+e^{a_i}}$
I_i=current sensory input

The Elman network is a recurrent neural network capable of learning grammar. Learning by backpropagation is insufficient and learning requires either dividing the training set into graded batches of increasing complexity, or equivalently by gradually increasing the window of recurrency. Early learning constrains the solution space to learn basic distinctions before learning more complex distinctions.

Appendix B: Evolutionary Algorithms

GENETIC ALGORITHMS

Genetic algorithms (GA) use the principle of biological evolution by natural selection on populations of individuals to produce better adapted populations. Darwinian evolution offers the key to adaptation to changing environments more efficiently than Lamarkian evolution. Genetic algorithms are general purpose nonlinear highly parallel probabilistic search algorithms based on the process of natural selection by Darwinian survival of the fittest and genetics through sexual recombination to optimise members of a population of individual structures [Holland 1962]. The structure’ represent the phenotypes of the population over a fitness landscape. GA's combine survival of the fittest (as measured by a cost function) with structured yet randomised information exchange. Genetic algorithms use historical information to speculate on new search points for improved performance and so guide searches. Whereas most optimisation and hill climbing methods are local techniques, the GA is a global and parallel search method that includes a rando’ised element to give near optimal searching in complex search spaces. GA's overcome the problem of gradient descent on the error surface which minimises a squared error criterion and may become trapped in local minima. The payoff function can be arbitrarily complex with no requirement for squared error criterion. It is similar to simulated annealing which is effectively a GA with a population size of unity. Whereas a single change in a computer program (other than parameter changes) ’ends to lead to major changes in the execution (usually detrimental), GA's use evolutionary variation and selection to search for a useful program P' from program P through structural alteration. A real-valued fitness function is assigned to each individual and evolution raises the average fitness of the population. Every environment is modelled as a fitness function returning value f(x) for each phenotype x with evolution finding value x* optimising f. One biologically valid approach is to associate evolutionary fitness to energy utilisation. If environmental resources are distributed uniformly in space and time, resources are shared by population leading to density dependence on fitness. At equilibrium for a constant population, expected population size, p:

$p = \frac{rE}{\varepsilon}(\eta + \eta\beta - \beta)$ where r=rate of replenishment of resources
E=energy
η=time average function of catalysed reactions of energy E=1 for optimal behaviour

Carrying capacity of the environment, $p_{\max} = \frac{rE}{\varepsilon} \rightarrow \frac{{}^{p\varepsilon}\!/_{rE} + \beta}{1+\beta}$

Random choice population level, $p\eta = \frac{rE}{2\varepsilon}(1-\beta)$

Expected reproductive fitness, $R_0 = \exp(no.offspring / lifetime)$

Number of offspring generated up to age a grows linearly with a:

$n(a) \approx \rho a$ where ρ=reproduction rate

Number of organisms of age a at any time follows the Euler-Lotka equation:

$$N(a) \approx \begin{pmatrix} pe^{-a} & \text{for} & a \le a_{\max} \\ 0 & & a > a_{\max} \end{pmatrix}$$

$$R_0 = \int_0^{a_{\max}} n(a).da \approx \tfrac{\rho}{2} a_{\max}^2$$

$$N(a_{\max}) \sim 1$$

Hence, $$\begin{aligned} pe^{-a} &\sim 1 \\ a_{\max} &\sim \ln(p) \end{aligned} \rightarrow R_0 \propto (\ln(p))^2$$

This links individual fitness and population size to measure selection pressure. Coevolution is faster and more robust than the use of a fixed fitness function. GA's mimic nature in that individuals serve as hypotheses concerning the properties of their environment. They do not utilise deduction or probabilistic analysis and they do not provide predictive power. They simply store historical information. Their behaviour involves inductive inference concerning aspects of that environment and validation is demonstrated through survival. Through successive generations, organisms become better predictors of their environment.

Genetic algorithms are computational representations of the process of Darwinian evolution by natural selection. Individuals (candidate solutions) of a population which are best adapted to their environment (the problem) survive in that environment and reproduce more than those individuals which are less adapted. The genetic algorithm encapsulates this evolutionary process – it has the advantage that it comprises a parallel search of a problem space defined by the fitness (performance) function. The population of individuals are typically coded as a population of binary strings to represent candidate solutions, though genetic programming adopts a coarser coding methodology based on a higher level computer language. The bit strings represent the "genes" of the individuals (based on binary rather than a quaternary code as adopted in biological systems). By applying genetic operators – reproduction by splicing sections of strings randonly, mutation by randomly point bit-flipping along the string, and inversion by reversing bit string sections – new populations are generated. Performed iteratively while reaping low-performing strings, the candidate solutions evolve towards effective solutions to the problem modelled by the fitness function. Such solutions are rarely optimal but do yield in general satisficing solutions, though there are classes of problems which are not well-suited to this method. GAs are similar to the LR-I learning rule in that successful candidates that are retained correspond to a reinforcement of 1 and those that are eliminated correspond to a reinforcement of 0. The GA involves five iterated steps which define each generation:

(i) selection
(ii) cross-over
(iii) mutation
(iv) fitness
(v) population statistics

GA's are general purpose, stochastic search algorithms based on the concept of evolution by artificial selection. Potential solutions to a problem are encoded as a population of bit strings. Genetic operators such as crossover and mutation operate on this population to generate a new population according to a numerical fitness measure which defines the desired robot behaviour. Each chromosome comprises a string of n positions (genes). Each gene assumes an allelic value 0,1,* (* is the wildcard). A population P of N individual chromosomes is initially randomly generated and genetic genetic operators act to modify randomly chosen individual chromosomes to generate new populations representing solutions to the problems encountered. The genetic operations include: (i) cross-over which cuts two chromosomes at random positions and recombines the two so that they are mixed into hybrid chromosomes; (ii) mutations which randomly changes some allelic values of chromosomes. This process represents a highly parallel search guided by the fitness function. the bucket brigade algorithm models the classifier population as an economic society. Every classifier pays an amount of its strength to other classifiers that invoked it and receives payment from all classifiers that it activates.

Genetic algorithms transform a population of objects each with an associated fitness value into a new generation using Darwinian evolution by natural selection. Each individual in the population represents a possible solution to a given problem. The encoding of the chromosome defines a mapping to the variables of the problem. Genetic algorithms differ from evolutionary programs in that the genes are encoded in binary. Within a genetic algorithm, each chromosome comprises genes, each gene being an instance of a particular allele. Crossover exchanges parts of two chromosomes, mutation randomly changes values at given locations within chromosomes, and inversion reverses the order of a section of the chromosome (latter is not much used in genetic algorithms). The cross-over randomly selects a number between 1 and L-1 using a uniform probability distribution where L=chromosome length. This defines the cross-over point. Each parent is split at this point and two parents are spliced into two offspring chromosomes. Individuals are probabilistically selected to undergo genetic operations according to their fitness measure.

In general, evolutionary algorithms utilise genes that possess a small range of allelic values, but more commonly are binary. GA's are genetic symbol strings of fixed length $a_1a_2....a_n$ constructed from a three valued allelic alphabet $A = \{0,1,*\}$ where * may be either 0 or 1 but is unspecified, ie. a chromosome. Neighbouring points are related through alteration of alleles at a single gene locus. For a gene string of length l with k allelic values there are $(k+1)^l$ possible combinatorial instantiations of strings. For a population of N strings there are Nk^l genotypes. The ratio of the maximum number of schemata instantiations in the population N over the total number of schemata is given by: $N(2/k+1)^l$. This is maximised when k is small hence the choice of binary strings. The initial population P(0) of N individuals chromosomes may be heuristic or random. It is an iterative scheme that maintains a constant size population of candidate solutions P(t) implemented as binary strings. The binary strings represent the states of the search space. Each iteration represents a generation during which the strings are evaluated on which basis a new population is generated. This iteration involves assigning a fitness value to each individual and creating a new population by application of genetic operators to individuals selected with probability based on the fitness. A mapping must erxpress each point in the search space of the problem to a given fixed length binary string. The binary representation must also be capable of expressing solutions to the problem. A mapping φ cannot be specified from the set of genotypes to the set of phenotypes so the fitness function is an indirect selection criterion with regard to the problem statement. A goal function provides the means for computing the probability that the gene string will be selected to contribute to the next generation. Evolution is driven by the fitness measure which assigns a fitness value to each binary string of the population. Fit strings that have larger goal function values are more likely to be selected, though inferior strings still possess a finite probability of selection. Alleles interact as patterns of co-adapted alleles (schemata) and the adaptation process effectively searches for such sets of alleles.

Genetic operators act to modify randomly chosen individual chromosomes to generate new populations. Each genetic operator causes movement across the fitness landscape. Future populations exploit structures that reflect regularity in their environment. The selection mechanism chooses strings in proportion to their performance relative to the rest of the population. A reproductive generator gives higher reproductive probability to more highly fitted individual chromosomes. Selection probability of undergoing reproduction based on performance: $P(p_i) = \frac{u_e(p_i)}{\sum_{j=1}^{n} u_e(p_j)}$

Expected number of offspring for an individual: $nP(p_i) = \frac{n.u_e(p_i)}{u_e[P(t)]}$ where u_e=utility measure. The average performance produces an average of one offspring. As the evolutionary process proceeds, the best performing strings will increase in proportion to the population.

The number of strings in a population of a given phenotype will increase at a rate proportional to its fitness (Holland fundamental theorem of GA's) [Vose 1991]. Holland's schemata theorem states that the number of strings in the population belonging to a given schemata will increase or decrease over time at a rate directly proportional to the observed performance of the schemata - this is an aspect of implicit parallelism as it applies to all schemata simultaneously. Successive applications of selection, recombination and mutation is an efficient method of using the information gained from a relatively small number of evaluated points to focus the population onto a region of high fitness where good solutions to the problem are to be found, ie. convergence. Termination of the genetic algorithm iteration may be triggered by finding an acceptable approximate solution.

Variation is introduced by means of genetic recombination operators, the most important of which is the crossover operator which acts to modify randomly chosen individual chromosomes to generate new populations. The crossover operator recombines individual chromosomes randomly while mutation operator randomly changes the allelic values of some genes. Crossover generates two new structures in the population by exchanging internal portions of the two parent structures at random points, ie. offspring p_k of parents p_i and p_j is produced by concatenating segments of each parent. One or two points are selected at random to create two children, eg. if $a_1....a_l$ and $b_1....b_l$ are operated on with crossover x in the range 1 to l-1 randomly gives $a_1a_2...a_xb_{x+1}b_{x+2}...b_l$ and $b_1b_2...b_xa_{x+1}a_{x+2}...a_l$. The one-point genetic algorithm cross-over may be represented thus where the cross-over point is at position 3/4:

Parent 1	A	B	C	D	E	F	G
Parent 2	a	b	c	d	e	f	g
Offspring 1	A	B	C	d	e	f	g
Offspring 2	a	b	c	D	E	F	G

If many cut points are used the probability of schemata disruption is increased so single or double crossovers are generally preferable. The new children replace the least fit members of the population. If each string is of length L, then there are 2^L possible combinations of populations. Crossover will only explore subspaces of the search space which are all ready represented in P(t). The mutation operator generates new individuals by randomly modifying one or more alleles of an existing individual. Each position has a fixed probability of being mutated independent of the other positions. Mutation ensures genetic diversity so that the search does not get trapped in local optima due to premature convergence. Alleles may be defined as ordered pairs which are treated as indiviSible units so that crossover points always occur between ordered pairs. inversion is an operator that can reverse the order of the ordered pair alleles. A co-adapted pair may be separated by a large distance increasing the probability that a crossover will separate the pair. Inversion reduces this distance and so reduces the possibility of seperation by crossover by promoting close linkage between successful alleles. However inversion is not much used [Jones 1992]. The crossover operation has pre-eminence over mutation in the evolutionary process. Reproductive cloning may also be used to copy individuals into new populations. Crossover can be restricted to small groups (demes) to encourage local groupings of genotypic similarity. A schema is a set of search space points with specific similarities. It is described by a string including the wildcard symbol. Each schema is represented according to the ratio of its schema fitness over all points within the schema to the average population fitness over all points in the population. The growth rate if each schema is optimal in maximising the payoff given the information available to the GA system. GA schema theorem states that the probability of losing any comb–nation of alleles is directly proportional to the distance between them - higher compaction reduces the probability of splitting. It has been sug“ested”that if two or more strings were closer together than a specified "niche" width then their goal function values may be shared between the group. For a population n of phenotypes x_i, the niche count N_i is a real number [1,n] and the shared value of the ith string: $V_s(x_i) = \frac{u_e(x_i)}{N_i}$ where u_e=fitness function. The shared value may be used to compute the selection probabilities $p_i = \frac{V_s(x_i)}{\sum_j V_s(x_j)}$. This ensures rapid adaptibility to random genetic drift. Each child replaces strings with the least shared values. Differential rates of survival and reproduction by fitter individuals is a central component of the GA. This provides a stable stochastic equilibrium for real time control purposes.

The genetic algorithm (GA) is characterised by 6 parameters: population size N, crossover rate R, mutation rate M, generation gap G, scaling window W, selection strategy S of which the major parameters are population size and the maximum number of generations to be run. The population size is a compromise between large population for diversity and small population for speed of convergence. Crossover rate C (number of members of the population that cross over each generation) is a compromise between a high rate for faster structure generation and a low rate for maintaining high performance solutions: CN structures undergo crossover per generation. Mutation rate should be low <0.05 as high mutation rate implies random exhaustive search: MNL mutations occur per generation. Generation gap controls the percentage of population to be replaced each generation: N(1-G) structures survive intact from P(t) to P(t+1). The scaling window involves the numerical performance criterion. The numerical performance value u(x) of a structure with input vector x where $u(x)=f(x)-f(x_{min})$ where f(x) is evaluated per string and $f(x_{min})$ is the minimum value of any structure in a generation. It is desireable to have maximum u(x). All structures with $f(x)<f(x_{min})$ are discarded. If $0 \le W \le 7$, $f'_{\min}$ is set to the least value of f(x) that occurred in the last W generations, ie. W=0 sets $f'_{\min}$ to the least value $f(x_{min})$ of the last generation whereas W=7 sets $f'_{\min}$ to the minimum of the first population. Selection strategy S denotes one of 2 selection strategies: S=P is pure selection where each structure in the current population is reproduced a number of times in proportion to its fitness performance. If S=E, an elitist strategy is adopted which initially uses pure selection and then stipulates that the best performance always survives intact into the next generation which might otherwise disappear. Tournament selection is another alternative whereby a specified group of individuals are chosen with random probability distribution from the population and the group with the highest fitness is selected. The group size can vary but 2-7 is commonly adopted. The’standard GA is GA(s)=GA(50,0.6,0.001,1.0,7,E) defining a space of 2^{18} GA's. Termination criterion comprises either satisfying problem-spec–fic success or the completion of a given maximum number of genera’ions - 50 being typical not including the initial random generation.

GA's are suitable for online control parameter estimation particularly for adaptive control [de Jong 1980]. Each point in the control input space C of allowable control inputs is represented as an individual binary string (or set of genes). There is a linear mapping of the structure of the system into the binary string such that numerical values of parameters specifying a control process are converted to binary representation and concatenated into a long binary string. The current population P(t) represents the current set of c’ntrol inputs. The scheme is to search for the optimal control inputs. GA's have been used extensively in optimisation problems as new sections of strings are generated to avoid local maxima. The performance function u_e over the control input space takes the role of genetic fitness for the control input population. It is based on how the control input affects the state of the process in the environment E and on measurements based on the state of the process. The adative strategy is evaluated in terms of the performance over time. The process performance measure is the feedback information indicating how well the controlled process is performing: $u_e=f(E,C)$. Fogel (1992) suggested that a suitable information measure such as the minimum description length description may offer a suitable criterion of fitness:

$L(\theta) = -\ln[f(y|\theta) + 0.5p\ln(n)$ where θ=parameter to be estimated
y=observation vector
$f(y|\theta)$ =likelihood function
p=number of adjusted parameters
n=total observations

If $x_1 \ldots x_m$ represents m control parameters of a complex process subject to constraints $a_i \le x_i \le b_i$, the values of x_i are represented as $L_i = \log_2[(b_i - a_i)\delta x_i]$ where δx_i is the level of resolution. The strings have a total length of $L = \sum_{i=1}^{m} L_i$ with each segment representing one of the control parameters. The expected number of offspring produced by an individual p_i varies in proportion to its performance value. For online parameter estimation, Grefensette (1986) su’gested that the best results were from GA=GA(30,0.95,0.01,1.0,1.0,E). GA's outperform standard optimisation routines in complex control spaces.

Genetic algorithms (GA) are suitable for online control parameter estimation particularly for adaptive control [de Jong 1980]. Genetic algorithms are nonlinear highly parrallel probabilistic search algorithms based on the process of natural selection and genetics. They combine survival of the fittest (as measured by a cost function) with structured yet randomised information exchange. They are symbol strings constructed from a three valued allelic alphabet $A = \{0,1,*\}$ where * may be either 0 or 1 but is unspecified. Each point in the control input space C of allowable control inputs is represented as an individual binary string (or set of genes). The current population P(t) represents the current set of control inputs. The scheme is to search for the optimal control inputs. They have been used extensively in optimisation problems as new sections of strings are generated to avoid local maxima. Genetic algorithms use historical information to speculate on new search points for improved performance and so guide searches. Whereas most optimisation and hill climbing methods are local techniques, the GA is a global search method that includes a randomised element to give near optimal searching in complex search spaces. It is an iterative scheme that maintains a constant size population of candidate solutions P(t) implemented as binary strings. The binary strings represent the states of the search space. Each iteration represents a generation during which the strings are evaluated on which basis a new population is generated. The initial population P(0) may be heuristic or random. Future populations exploit structures that reflect regularity in their environment. The selection mechanism chooses strings in proportion to their performance relative to the rest of the population. The performance function u_e over the control input space takes the role of genetic fitness for the control input population. It is based on how the control input affects the state of the process in the environment E and on measurements based on the state of the process. The adative strategy is evaluated in terms of the performance over time. The process performance measure is the feedback information indicating how well the controlled process is performing: u_e=f(E,C). Variation is introduced by means of genetic recombination operators, the most important of which is the crossover operator. This generates two new structures in the population by exchanging internal portions of the two parent structures at random points, ie. offspring p_k of parents p_i and p_j is produced by concatenating segments of each parent. If each string is of length L, then there are 2^L possible combinations of populations. Crossover will only explore subspaces of the control space which are all ready represented in P(t). The mutation operator generates new individuals by randomly modifying one or more alleles of an existing individual. If $x_1 \ldots x_m$ represents m control parameters of a complex process subject to constraints $a_i \le x_i \le b_i$, the values of x_i are represented as $L_i = \log_2[(b_i - a_i)\delta x_i]$ where δx_i is the level of resolution. The strings have a total length of $L = \sum_{i=1}^{m} L_i$ with each segment representing one of the control parameters. The expected number of offspring produced by an individual p_i varies in proportion to its performance value.

Selection probability of undergoing reproducction based on performance: $P(p_i) = \frac{u_e(p_i)}{\sum_{j=1}^{n} u_e(p_j)}$

Expected number of offspring for an individual: $nP(p_i) = \frac{n.u_e(p_i)}{u_e[P(t)]}$

The average performance produces an average of one offspring. As the evolutionary process proceeds, the best performing strings will increase in proportion to the population. Termination of the genetic algorithm iteration may be triggered by finding an acceptable approximate solution. The mean converge time for a GA for a population size of N, zero mutation, uniform recombination of n loci is given by: $1.4N(0.5\ln(n)+1.0)^{1.1}$ generations.

The genetic algorithm (GA) is characterised by 6 parameters: population size N, crossover rate R, mutation rate M, generation gap G, scaling window W, selection strategy S. The poulation size is a compromise between large population for diversity and small population for speed of convergence. Crossover rate (number of members of the population that cross over each generation) is a compromise between a high rate for faster structure generation and a low rate for maintaining high performance solutions: CN structures undergo crossover per generation. Mutation rate should be low <0.05 as high mutation rate implies random search: MNL mutations occur per generation. Generation gap controls the percentage of population to be replaced each generation: N(1-G) structures survive intact from P(t) to P(t+1). The scaling window involves the numerical performance criterion. The numerical performance value u(x) of a structure with input vector xwhere u(x)=f(x)-f(x_{min}) where f(x) is evaluated per string and f(x_{min}) is the minimum value of any structure in a generation. It is desireable to have maximum u(x). All structures with f(x)<f(x_{min}) are discarded. If $0 \le W \le 7$, $f'_{\min}$ is set to the least value of f(x) that occurred in the last W generations, ie. W=0 sets $f'_{\min}$ to the least value f(x_{min}) of the last generation whereas W=7 sets $f'_{\min}$ to the minimum of the first poulation. Selection strategy S denotes one of 2 selection strategies: S=P is pure selection where each structure in the current population is reproduced a number of times in proportion to its performance. If S=E, an elitist strategy is adopted which initially uses pure selection and then stpulates that the best performance always survives intact into the next generation which might otherwise disappear. The'standard GA is GA(s)=GA(50,0.6,0.001,1.0,7,E) defining a space of 2^{18} GA's. For online parameter estimation however, Grefensette (1986) su'gested that the best results were from

GA=GA(30,0.95,0.01,1.0,1.0,E). GA's outperform standard optimisationroutines in complex control spaces.

Modified genetic algorithm has following properties as neural network learning rules [Jeong & Lee 1997]:
Fitness:

$$F' = \begin{cases} kF_{av} - F \geq kF_{av} \\ F - otherwise \end{cases} \quad \text{where } k>1$$

Mutation probability:

$$p_m(i_{gen}+1) = \begin{cases} p_{m0} - cons\tan t\_fittest \\ p_{m\_low} - p_m(i_{gen}) \times k' \leq p_{m\_low} \\ p_m(i_{gen}) \times k' - otherwise \end{cases} \quad \text{where } i_{gen}\text{=generation number, } k'<1$$

Selective reproduction in genetic algorithms may be of a number of different types: roulette wheel method selects individual phenotypes according to a probability given by:

$$p_j = \frac{F_j}{\sum_{i=1}^{n} F_i}$$

The expected number of offspring for individual j is Np_j where N=number of individuals in population. This method suffers from random genetic drift when all individuals obtain similar fitness values. Rank based selection involves individuals being ranked and the probability of generating offspring is proportional to their rank rather than fitness. A variation on this is truncation selection whereby the top ranked m individuals make o copies of their offspring such that N=m x o. Tournament selection determines offspring on the basis of two randomly selected individuals. If the random number r is less than threshold T, individual with higher fitness generates offspring, otherwise the other individual makes an offspring. This does not require total population fitness computations. Elitism is tournament selection which only picks the higher fitness individual. Once the new population has been generated, offspring are randomly paired, crossed-over and mutated. Cross-over may be one point or multi point cross-over, typically one-point cross over. Mutation is applied randomly with a low probability. For binary codes, this is a bit flip operation. For real values, a random substitution is made from the range. In distributed genetic algorithms, subpopulations for exploring different solutions to the same problem prevent premature convergence. For a chromosome length l, fitness landscape has l+1 dimensions, the height being given by the fitness. Schema theory suggests that genetic algorithms explore fitness landscapes by generating partial subsolutions (building blocks) that are represented by a family of strings. Consider a population of N individuals with a binary representation for each chromosome of length l – there will be $n2^l$ schemata where $1 \leq n \leq N$. Due to this, genetic algorithms effectively process N^3 different schemata despite only N strings being evaluated (implicit parallelism). Schemata with short lengths have higher probability of surviving without being broken up by cross-over. Small random mutations which have no effect on fitness can move the chromosome along neutral ridges in the fitness landscape to new solutions. Neutral evolution favours the presence of junk DNA and plays an important role when there is an indirect encoded mapping between the genotype and phenotype such as growing instructions. Neutral networks yield punctuated equilibrium type evolutionary stasis-rapid evolution phases. This is the basis for SAGA – species adaptation genetic algorithm – which allows variable length genotypes. The SAGA (species adaptive genetic algorithm) involves the use of populations with genotyopes which are rather similar, ie. fairly well converged [Harvey 1996a,b]. This allows incremental evolution even when the problem itself changes over time including the implementation of changing genome lengths. In this case, recombination is less important than mutation as the dominant genetuc operator. The converged population is centred around some local optimum. The mutation rate has to be sufficient to ensure further progress but not too high that historical information from earlier evolution is lost. The optimal mutation rate will enable the search to follow along high ridges in the fitness landscape – these are regions of neutral networks.

Evolution is a means to search through a large number of potential solutions to a problem in parallel, eg. coefficients of an equation. Genetic algorithms transform a population of objects into a new population on the basis of their fitness values according to the principle of biological evolution. The genetic algorithm may be represented as a dynamical system of the form [Altenberg 1994]:

$$x_i' = \sum_{jk} T(i \leftarrow j,k) \frac{w_j w_k}{\overline{w}^2} x_j x_k$$ where x_i =frequency of type i in population

x_i‘ =frequency of type i in next generation
w_i =fitness of type i

$\overline{w} = \sum_i w_i x_i$ =mean fitness of population

$T(i \leftarrow j,k)$ =probability that offspring of type i is produced by parental types j and k as a result of genetic operations=transition matrix

The genetic algorithm comprises of three main components [Mitchell & Taylor 1999]:

(i) population of candidate solutions to a problem (chromosomes) represented as strings (genes), usually binary strings;
(ii) fitness function which computes a numerical performance metric to each chomosome
(iii) set of genetic operators applied to chromosomes to create new populations – these include selection (asexual reproduction), cross-over (sexual reproduction) and mutation.

Reproductive fitness provides the basis for differential selection. The fitness function which provides the performance metric for determining fitness defines the problem while the individuals of the population represent potential solutions to the problem. In genetic algorithms, the individual solutions are encoded as fixed length bit strings representing chromosomes. The alphabet size is typically binary. The representation scheme is defined by the mapping of the genetic code to the phenotype. The genetic evolution process is determined by the population size and the maximum number of generations to be run (termination criterion). The genetic algorithm proceeds thus:

1. generate a random initial population n of fixed-length bit strings (chromosomes)
2. perform the following iterative loop until termination criterion has been satisfied:
    a. compute fitness value f(x) to each individual chromosome x using fitness function f
    b. create new population by applying three genetic operators according to a probability based on fitness f(x):
        (i) reproduce a string by copying it into the new population
        (ii) create two new offspring string from two parent strings with probability p_c using cross-over at a random point (crossover)
        (iii) create new string by randomly mutating an existing string with probability p_m at a randomly chosen point
3. best string with the highest fitness should represent a solution to the problem

In pseudo-code this may be represented:

```
Begin GA
  g=0  !generation counter
  Initialise population P(g)
  Evaluate population P9G0  !compute fitness value
  While not done do
    g=g+1
    select P(g) from P(g-1)
    crossover P(g)
    mutate P(g)
    evaluate P(g)
  endwhile
end GA
```

A genetic algorithm is run for typically 50-500 generations. It may be necessary to perform independent runs with different random number seeds to obtain a satisfactory result. During the reproductive operation, individuals are selected for copying into the next generation probabilistically based on their fitness – the higher the fitness the higher the probability of selection. The genetic operator (emulating sexual reproduction) selects two parents probabilistically based on their fitness and cross over randomly selects the cross-over point between 1 and L-1 using a uniform probability distribution. The two sections created from each parent are swapped to create two new offspring. Mutation creates new individuals but the mutation rate is set at a low level. The genetic algorithm searches for a high fitness string that gives high values for the fitness function. According to schema theory, if the size of the population is n then n^3 schema are processed in parallel. If short segment schema which encode useful functions occur in the population, they will be used as building blocks by recombination to form fitter individuals in the next generation. Elitist strategies can reduce diversity and generate suboptimal solutions [De Jong & Spears 1993]. The chief problem with genetic algorithms is in dealing with "hard" multimodal problems, eg. Rastrigin's function $f_r(x) = \sum_i \left(x_i^2 - 10\cos(2\pi x_i) + 10\right)$ and Schwefel's function $f_s(x) = \sum_i \left(-x_i \sin(\sqrt{|x_i|}\right)$ [Salomon 1999].

The genotype is defined by the chromosomes whereas the phenotype defines the whole organism that is the result of expression of those chromosomes. The process through which the genes define the phenotype of the organism is through embryonic development. This requires an encoding scheme of genotype-phenotype mapping which describes growth which occurs through cell division. Daughter cells which propagate from parent cells will essentially be the same but will be subject to three constraints [? 1988]:

(i) identical genotypes (assuming no mutation)
(ii) phenotypic variation due to the environment
(iii) cell specialisation and differentiation through genes switched off

The growth rules which are the same for all cells of the organism may be defined as production systems (condition-action rules) of the form:

$X + K_i \xrightarrow{w} K_j K_k$ where K=cell phenotypes
X=local content
w=weight

The condition of the rule is satisfied if the cell of type K_i and the context matches X. The action of the rule is to replace the parent call with two new daughter cells with phenotypes K_j and K_k respectively. X in its simplest form may be adjacency and spatial relationship to particular kind of cell in its environment. Alternatively, X may be detector which detects signals emitted by other cells further afield, such signals encoding a list of phenotypical properties. X may also encode physical characteristics of the environment such as temperature. Differential development depends on the selection for expression of different rules in different cells. This consists of two steps: a match step in which the cell identifies those rules which are satisfied, and the decision step in which the cell chooses a single rule from the match set. The decision is based on the product:

Excitation of rule, $e = w.ns_i$ where w=weight

s_i=signal intensity
n=number of signals

The cell selects the rule on the basis of excitation level of the rule. These rules may be reproductive, inhibitory or deletion operators. If a large number of reproductive operators are operating, the embryo will grow but the relative excitation of inhibitory and deletion rules will increase slowing the rate of growth until an equilibrium size is reached. The equilibrium size is given by:

$n^* = \left(\frac{1}{s}\right)\left(\frac{w_r}{w_d}\right)$ where $w_{r,d,i}$ = probability of reproduction/deletion/inhibition

Net growth rate is independent of equilibrium size:

$$\frac{dn}{dt} = n\frac{(1-n/n^*)}{1+(w_i/w_d+1)(n/n^*)}$$

The process may be encoded within a genetic algorithm (similar to a classifier system) with a population of egg cells each with a random phenotype. Each egg undergoes development and on reaching equilibrium, each would be subjected to a fitness test. Fitter eggs would be copied into the next generation according to the normal genetic algorithm process. An interpreter is required to relate genotype to phenotype properties which may be pre-defined as in classifiers.

Lamarckian evolution differs from Darwinian evolution in that the evolution of traits are modified through the lifetime of an individual and passed onto the genotype of the next generation. However, biological systems lack mechanisms for implementing such processes. Lamarckian evolution requires both a developmental/learning process and a means for encoding that learning into the genotype. Neural networks are the most commonly employed learning mechanisms. Randomly coded Hopfield networks can learn and store a number of memories defined by 0.15 times the number of nodes in a fully connected system. Hebbian learning doubles this capacity. Indeed, learning can increase the space of solutions more effectively than Darwinian evolution alone. If encoded in a genetic algorithm, the maximum exploration is given by the product of the total number of members of the population and the number of generations. If neural networks learn through a number of trials at each generation, the space explored is the product of the total number of members of the population, the number of generations, and the number of trials [Mitchell & Taylor 1999]. The Baldwin effect provides the basis of genetic assimilation with accelerated evolution. Leaning as an adaptive mechanism may generate useful traits which increase fitness. Thus, valuable configurations of alleles may arise which prove valuable – although the trait itself is not passed on genetically, the genetic configuration underlying it will be. Thus learning and adaptation within the organism’s lifetime leads to increased survival and so spread the genetic variation that produces the trait. The Baldwin effect is an indirect effect of learning on evolution [Mitchell & Forrest 1993]. Organisms best able to learn advantageous behaviours will have the most offspring and increase the frequency of genes for learning ability. This can lead to a genetically encoded trait that was learned. The genetic algorithm has been used to model the Baldwin effect such that the genetic algorithm encoded the learning properties of a population of neural networks. Learning alters the shape of the fitness landscape by making it smoother.

CLASSIFIER SYSTEMS

Classifier systems offer a hybrid approach based on condition-action rules (classifers) which is capable of learning through credit assignment through a bucket brigade algorithm and rule discovery through genetic algorithms [Holland 1986, Booker et al 1989]. As if-then rules, classifier systems are computationally complete as Turing-equivalent [Geyer-Schultz 1995]. There are three separate components: the performance system which interact directly with the environment and comprises a highly parallel set of classifier rules, a credit assignment system using the bucket brigade algorithm to evaluate the rules, and a rule discovery system to generate new rules by combining building block units of rules through the genetic algorithm. An input interface translates the current state of the environment into stan'ard messages based on bit values. The classifier rules define the system's procedures. A message list contains all current messages (blackboard working memory) and an output interface which translates the messages into effector actions. Classifiers check whether conditions are met by messages in the message list in parallel – if so, classifiers attempt to post messages specified by their action parts.

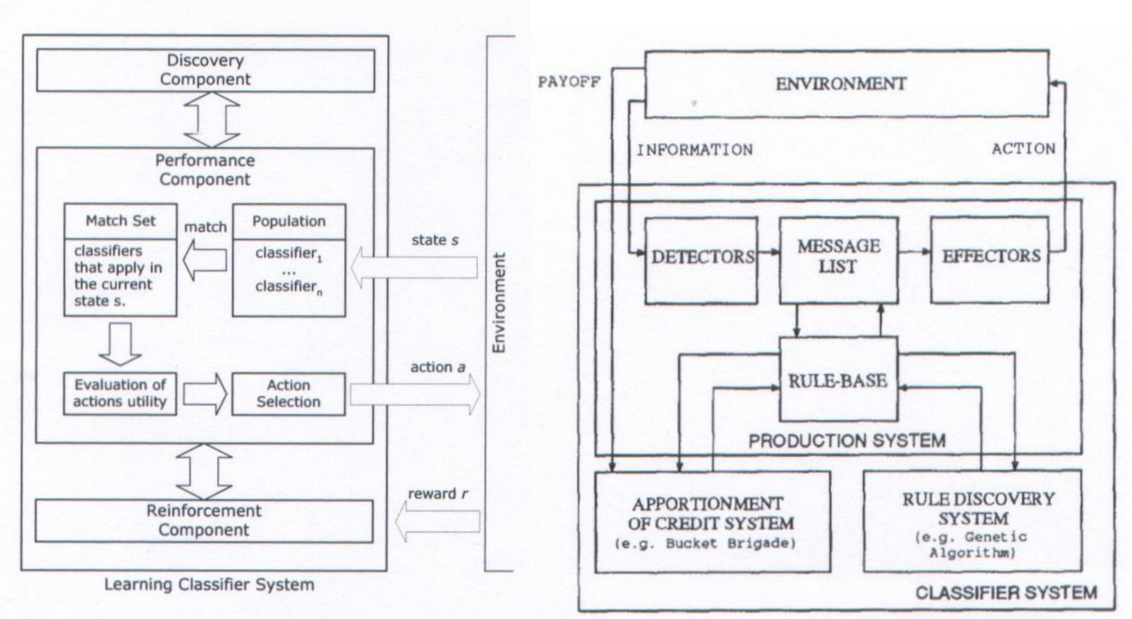


Fig B-1 (a) Learning classifier system and its interface to the environment; (b) architecture of a Michigan type classifier

All the classifier rules are based on the alphabet {0,1,*} where * is the wildcard. A message m is k symbol string from {0,1,*} comprising a condition c from {0,1,*} and an action from {0,1,*}. The input interface produces binary messages based on the detection of objects in the visual field involving classifiers which determine the output behaviour. The leftmost loci of the classifier specifies the tag to identify the origin of the message. Two classifiers are coupled if a message produced by the first classifier satisfies a condition of the second classifier. Thus chains of coupled classifiers can be generated. Networks can be built up with tags acting as pointers to addresses to couple the rules together to generate branches of reasoning. Boolean logical combinations such as AND, OR, NOT may be realised through a combination of couplings to form semantic networks. With spreading activation, the message list comprises a global blackboard database into which messages are posted to form arbitrary hierarchical and hetarchical associations between the rules such that the classifier uses the condition-actionn rules that interact by passing messages. Credit assignment determines the success of rules. The bucket brigade algorithm assigns a numerical strength quantity to each classifier. The strength of the classifier is adjusted to reflect its overall usefulness on the basis of competition (fitness). The bucket brigade algorithm is an economic system based on bargaining where the classifiers and environment act as economic agents which produce and consume messages within a marketplace degined by auction. The auction has three phases – bidding where agents make bids, competition which determines the winning agent, and clearing where transactions are completed and payments made. The classifier makes a bid in terms of its strength and only the highest bids get their messages to the message list. Bid B=bRs where s=classifier strength, R=specificity=number of non * symbols in the condition, b<1. The bid determines the probability that the classifier posts its message according to:

$P = \frac{\beta_j}{\sum_{i=1}^{n} \beta_i}$ where β_j=effective bid of classifier j

Each rule deals with its suppliers which satisfies its conditions and its consumers with conditions satisfied by the messages. When a rule wins a bid, it pays out part of its strength to its suppliers so that active rules behave as suppliers to its consumers and receiving payment for them. A wining classifier's strength is reduced by the amount bid: s(t+1)=s(t)-B(t) while suppliers have their strengths increased by s(t+1)=s(t)+aB(T) where a=1/(number of rules). Hence, fitness changes are backpropagated through the rule network. The rule discovery process utilises Gas which recombine components through cross-over from high strength parent classifiers to form offspring to displace weak classifiers to drive the overall s(t) upwards. To ensure that unless rules which send messages satisfying their own conditions (parasites), all rules should be taxed according to their strength. Stable populations form default hierarchies where general rules with many * cover the most frequent cases and more specific rules to cover exceptions. The GA effectively implements a generate-and-test process in parallel. Classifier systems are particularly suited to changeable enironments requiring incremental learning by adding new rules.

Classifier systems are parallel, message-passing, learning systems which model stimulus-response rules. They comprise four structural components:

(i) input detectors
(ii) output effectors
(iii) classifier list C of condition-action rules
(iv) message list M of active classifiers

The major execution cycle comprises the following activities:

(i) activation of input detector messages to message list
(ii) activation of classifier list to select winning classifiers
(iii) activation of output effectors depending on new messages
(iv) credit assignment to update strengths of rules
(v) rule discovery by genetic algorithm
(vi) message list updating by new messages

Classifiers can be divided into two parts: set of rules (classifiers) and a message list. The rules define responses while the message list contains the inputs from the external environment. The message inputs are in binary form of fixed length defining sensor values. Other messages in the message list are supplied internally by the rules. The message list is dynamic as external inputs change or rules generate new internal messages. Classifier rules comprise of multiple parts: one or more conditions, an action, and a strength. The conditions and actions are also binary strings of the same length as the messages but include the * wildcard which will match with anything. More * in a rule are more general than rules with fewer *. Matches are searched for between conditions and messages in the message list. If a match is found, the rule posts its action to the message list. This generates a series of internal messages. Some rule actions act as effectors to generate outputs. Strength of a rule

indicates its value to provide the basis for learning. Associated with each classifier is a strength which reflects its utility based on its previous experience. If a rule generates a useful response, it gains strength, otherwise it loses strength. Strong rules are favoured over weaker ones. A rule may trigger a chain of internal messages eventually leading to a useful response. A bucket brigade algorithm manages credit assignment among competing classifiers by altering the strength of each rule. An economic structure is generated whereby the classifier system identifies and use the rules that have been successful in the past. The value of each rule is established whereby rules pay each other and strength is passed back from the output. A rule that matches a message in the message list places a bid proportional to the product of its strength x_i and the specificity of the match m_{ij} which defines the number of non-*: $B_i=c.m_ix_i$. If a rule posts a message, it pays the rule that supplied the message that it is matched to an amount equal to the bid. All rules are taxed according to their strength so that rules that do not post messages decline in strength. The genetic algorithm is used to discover useful rules based on intermittent feedback from the environment. The genetic algorithm treats the strength as the rule's fitness. Classifiers are randomly selected according to their strength for genetic operations. The genetic algorithm modifies high strength rules through cross-over and mutation. Weakest rules are replaced by the offspring. The genetic algorithm provides the inductive learning mechanism which builds default hierarchies of rule clusters.
Change in strength of ith classifier due to bid payments is given by:

$$\Delta x_i = -c\sum_{j=1}^{N+n} m_{ij}x_i f_j H(m_{ij}x_i - T) \text{ where T=threshold}$$

H(x)=1 for x>0
=0 otherwise
f_j=1 if classifier posted on message list
=0 otherwise
c=bid fraction of strength

Change in strength of ith classifier due payments from other classifiers:

$$\Delta x_i = c\sum_{j}^{N} m_{ji}x_j f_i H(m_{ji}x_j - T)$$

The total effect including taxation is given by:

$$\Delta x_i = c\left(\sum_{j=1}^{N} m_{ji}x_j f_i H(m_{ji}x_j - T) - \sum_{j=1}^{N} m_{ij}x_i f_j H(m_{ij}x_i - T)\right) + f_i P^t - k_2 x_i$$

where P=performance function
k_2=tax rate

There are two credit assignment mechanisms – bucket brigade and profit sharing plan. The bucket brigade algorithm is incremental while profit sharing is episodic where an episode is defined as the time interval between receipt of two successive rewards. Bucket brigade algorithm requires less computation resources but profit sharing has better performance. For profit sharing, bid is given by: $B_i=b.S_i$ where b=risk factor, S_i=strength=S_{i-1}-B_i+bE_i, E_i=external reward. Action-oriented economic updating provides a further variant on these two algorithms that provides goal relevance [Weiss 1995].

The classifier system is a learning system in which sets of condition-action rules compete to control a system and earn credit based on reinforcement from the environment. The accumulated credit (strength) determines its influence. Classifier system condition-action rules are discovered through genetic algorithms, thus providing the means for implementing induction. A learning classifier system learns by interacting with the environment from which it receives feedback as a reward.

Learning occurs by attempting to maximise this reward. There are for main components to a earning classifier system [Holmes et al 2001]:

(i) finite population of condition-action rules (classifiers) that represent current knowledge
(ii) performance assessment which determines interaction with the environment
(iii) reinforcement (credit assignment) which distributes reward received from the environment to the classifiers responsible for the rewards
(iv) discovery which is responsible for finding better rules using genetic algorithms

Classifiers have two associated measures – prediction (strength) estimates the classifier utility in terms of the amount of reward if the classifier is activated; and, fitness estimates the quality of the classifier as information about the problem and determines its reproductivity. The system receives input on the current state of the environment and builds a match set (M) containing the classifiers in the population (P) whose all-conditions match the state of the environment. The system evaluates the utility of the actions in the match set – one action is selected according to certain criteria and acted upon in the environment. The roulette wheel decision is based on the probability equal to the classifier's bid divided by the sum of bids of all classifiers whose conditions are satisfied (ie. the match set). Alternatively, probability might be given by:

$$p(a_i) = \frac{e^{S_{M_i}/T}}{\sum_k e^{S_{M_k}/T}}$$ where T= annealing schedule beginning high and slowly decreasing

The noisy auction decision has gaussian noise added to each bid to vary the degree of determinism and the emphasis on exploration/exploitation according to the degree of uncertainty. Bids of classifiers whose payoff amount was reliable will be treated as deterministic while those with uncertain payoff amounts will be stochastic. The action set (A) is formed comprising all classifiers which have the selected action. This action is then performed on the environment. The system receives a reward from the environment as a consequence of the action. Reinforcement distributes the reward among the rules responsible for the reward thereby updating their strength. This may be implemented using the bucket brigade or Q-learning algorithm. Q-learning involves learning a policy that maximises the discounted sum of future rewards. It uses the Widrow-Hoff rule to update the policy. The bucket brigade algorithm distributes credit to sequential chains of classifiers and is appropriate under infrequent payoff conditions. A fraction of the strength received by a classifier is passed back to the previous classifier that invoked it. The implicit bucket brigade algorithm eliminates the bid competition. A fixed fraction $0<\beta<1$ of the strength (bid) S_A of each member of (A) is deducted from the member's strength and placed in an initially empty bucket (B), ie. βS_A. A reward R received from the environment adds a fraction $\gamma R/|A|$ to the strength of each classifier in (A) where $0<\gamma<1$ and $|A|$=number of classifiers in (A). Classifiers in the previous action (A)$_{-1}$ alao have their strengths increased by $\gamma(B/|A_{-1}|)$ where B=amount in bucket. The effect on total strength S_A over time is given by: $S_A \leftarrow S_A - \beta S_A + \beta R + \beta\gamma S_{A+1}$. In order to penalise matching classifiers which do not advocate the successful action, the strengths of classifiers in the difference set (M)-(A) have a tax levied to reduce their strengths by $\tau\approx\beta$ - however, if this is too high, sub-optimal convergence can occur. A classifiers bid is used to determine whether the classifier is activated while the payout is the total amount that a classifier pays to the classifiers that invoked it, differentiating between bid and payout. It is difficult to maintain long bucket brigade chains. This is particularly important as there may be extensive action sequences before environmental payoff is received. Furthermore, earlier members tend to suffer from reduced strength due to reduced payoff and more frequent invocation of later classifiers. The profit sharing plan overcomes some of these difficulties by distributing payoff to all earlier classifiers. Periodically, the discovery component uses a genetic algorithm to select two classifiers from the population with a probability dependent of their fitnesses. It applies cross-over and mutation to generate two new classifiers which are inserted into the population replacing two classifier rules selected with a probability inversely proportional to their strengths. Offspring possess the average strength of their parents. Learning classifiers can adapt online using the genetic algorithm within rapidly changing environments. Invocation of the genetic algorithm depends on the problem. Generalisation of rules to apply to many environmental situations may be achieved. Classifiers have a tendency for overgeneralisation which suggests that payouts should not be dependent on a classifier's specificity [Wilson & Goldberg 1989]. Hierarchical, modular decomposition of classifiers helps to reduce bucket brigade chain lengths. Default general rules may be used to cover most normal situations but with more specific rules for situations when the default would not be appropriate. However, high taxation is required to overcome the tendency towards overgeneralisation. When the system cannot match the environmental inputs, ie. (M) is empty, a matching classifier (with probabilistically determined number of *) is created with a randomly chosen action and a strength equal to the population average (covering operation). It is placed in the population and a low strength classifier deleted. Clusters of classifiers – corporations – avoid competition between classifiers within the corporation as only the corporation as a whole can be reproduced or deleted as a unit. Complexity of learning grows as a low order polynomial of the complexity of the problem. ZCS (zeroth level classifier system) eliminates the message list and is characterised by the following parameters: N – population size; P_* - probability of * at allele position in condition of classifier; S_0 – classifier strength; β - learning rate for strength update; γ - discount factor; τ - fraction of strength deducted from (M)-(A); χ - probability of crossover per invocation of GA; μ - probability of mutation per allele in offspring; ρ - average number of new classifiers generated by GA per time step; ϕ - if strength of (M) < ϕ x mean strength of (P), covering with GA occurs [Wilson 1994]. ZCS resembles Q learning which in turn resembles the Widrow-Hoff learning rule. XCS has evolved from ZCS and introduces a number of changes to LCS [Wilson 1995, 1998]:

(i) fitness of classifiers depends on accuracy of classifier's prediction rather than prediction itself
(ii) discovery component acts on a subset of classifiers which apply to the same situation rather than the whole population (environmental niche)

Each XCS classifier has three parameters: prediction p_j, error e_j, and fitness f_j. Prediction estimates the Q-learning-like payoff P when the classifier matches and its action is selected using the Widrow-Hoff rule: $p_j \leftarrow p_j + \beta(P - p_j)$. Error is an estimate of the error in p_j also according to the Widrow-Hoff rule: $e_j \leftarrow e_j + \beta(|P - p_j| - e_j)$. Classifier fitness is based on the accuracy of payoff prediction with accuracy given by $k_j = e^{\ln \alpha (e_j - e_0)/e_0}$ for $e_j > e_0$, otherwise $k_j=1$, e_0=accuracy threshold. Relative accuracy k'_j is computed for each classifier in the action set by dividing k_j by the sum of k_j. This gives a fitness for each classifier according to the Widrow-Hoff rule: $f_j \leftarrow f_j + \beta(k_j' - f_j)$. The fitness for the classifier depends on the accuracy of the payoff. Similarly, the GA is operated over the action sets (A) and $(A)_{-1}$ which increases the proportion of accurate, maximally general classifiers in the population. This eliminates undesirable competition between classifiers in different match sets. A numerosity value is assigned to each classifier according to how many times it is generated by the GA (numerosity of 1 defines its first evolution) to ensure that multiple copies of the same classifier are not placed in the population – however, it increases the proportion of payoff it receives as if it comprises n copies. Deletion of such a classifier decrements its numerosity by one. Internal message list may add extended capabilities to retain long-term memory. The XCS is capable of solving more complex problems with compact solutions. It is particularly suited to multi-step Markovian environments with delayed reinforcement (class 1 environments) to which reinforcement learning is applicable [Wilson 1995]. Woods2 was a class 1 environment with two kinds of food and two kinds of rock with an animat capable of sensing its environment and objects in the 8 neighbouring cells. The animat cannot occupy cells occupied by rocks but can occupy an empty cell and a cell with food (for which it receives a reward). XCS coped reasonably well within such a complex environment.

Control architecture based on the hierarchical classifier system uses both reactive and planning rules to implement a motivationally autonomous animat that chooses its actions according to the expected consequences [Donnart & Meyer 1996]. The animat was simple with three proximate sensors (discrete front, right, left) and three motor directions (discrete front, right, left) and navigated a 2D environment. Binary reactive rules take the form: IF <sensory data> and <goal direction> THEN <action>. Sensory data indicates presence (1) or absence (0) of obstacle. Motor action is defined similarly. The planning module binary rules take the form: IF <sensory data> and <current task> THEN <new task>. Tasks are encoded as coordinates. Context generator is a list of tasks to be performed. Internal learning module defines reinforcement altering rule strengths depending on satisfaction of animat according to progress towards the goal:

$s(R,t+1)=(1-\alpha)s(R,t)+\alpha.S$ where s=strength of rule R

S=satisfaction= $\frac{d(t)-d(t-1)+d_{\max}}{2.d_{\max}}$

d(t), d(t-1)=distance to current goal at t, t-1

d_{max}=maximum distance

A profit sharing plan was used to distribute payoffs. The motivational state depends on the internal state such as energy level.

GENETIC PROGRAMMING

Koza (1991) introduced the notion of genetic programs, an alternative to genetic algorithms. Genetic programs use context-free grammar languages to generate label-ordered program trees rather than strings to allow subtree substitution. Any computer program is translated into a parse tree which is converted into machine code. Genetic programs initially creates computer programs at random and this manipulates them by various genetic operators. Genetic programming involves the search for the solution to a problem in the hyperspace of all possible compositions of functions that can be composed. Typically, S (symbolic) expressions of LISP are used as a parse tree. S-expressions are thus rooted trees with ordered branches. The principal genetic operator is cross-over that swaps subtree portions of the parse tree from two parent to form two offspring programs. The point of swapping is randomly selected in both parents. As entire subtrees of such programs are swapped, the offspring are syntactically valid LISP S-expressions. Symbolic expressions are the only syntax in LISP. LISP offers a means of representing trees and stacks as special cases of directed graphs. Each non-terminal node is represented by a linked list of its children. Any LISP expression is a rooted, labelled tree with ordered branches. This is the parse tree used by compilers to translate the program. Genetic programming is an extension of the genetic algorithm in which hierarchical computer programs undergo adaptation. The individuals of the genetic population are hierarchical compositions of functions and arguments of LISP. The symbolic S-expressions of LISP correspond to a compiler parse-tree of logical relations AND, OR, NOT into hierachies. Syntactic mutation of LISP programs still generate meaingful LISP programs while point mutations of genetic algorithms with their higher resolution are almost always detrimental. A single LISP mutation is equivalent to many coordinated small mutations at machine code level. The search space in genetic programming is the set of all possible computer programs appropriate to the problem. Five steps prepare genetic programming to problems by determining the set of terminals, the set of primitive functions, the fitness measure, the parameters for controlling the run, and the criterion for terminating the run. Each computer program is a composition of functions from the function set F and terminals from the terminal set T. The primary parameters for controlling the run are the population size M and maximum number of generations to be run G. Populations of 1000s of computer programs are bred genetically using the Darwinian principle of survival and reproduction of the fittest with genetic crossover operator providing the mating of computer programs. Each individual is evaluated by relative fitness. The populations mutually bootstrap each other. Fitness of a program can be measured by the error between the result produced and the correct result. Error is usually measured as a sum over a number of combinations of the inputs to the program, ie. over a number of different fitness variables. Fitness can be measured in terms of Minkowski or Euclidean distance. Fitness may be computed implicitly by allowing pograms to interact in a simulation environment and among themselves. Offspring are composed of subexpressions (subtress, subprograms, subroutine, functions) from their present programs. Recombining random parts of effective programs may yield more effective programs. The population of offspring replace the old population over many generations. The parents are rooted, labelled trees with ordered branches. Internal nodes of the tree correspond to functions and external leaves correspond to terminals, ie. input data. The basic genetic operator is the cross-over which copies individuals with a probability proportionate fitness from one generation to the next by producing two offspring using parts from both parents. Since the programs from hierarchical trees new offspring are generated by exchanging sub-trees between the two parents so that syntactically and semantically valid LISP S-expressions become offspring. Crossover exchanges subtrees (subroutines, subfunctions) between two parents. Crossover points are chosen randomly but ensure the viability of programs. The crossover creates two new offspring programs using parts of the parental programs. A mutation operator operates only on one parent S-expression by randomly inserting a randomly generated sub-tree robot (possibly of depth 0) to re-introduce diversity to the population. Other operations may be implemented – duplication, insertion and deletion. Two or more populations of computer programs co-evolve simultaneously so that each population acts as the environment for the other population – the fitness measure is provided by the environments. Both populations of individuals co-evolve to higher levels of absolute fitness without the need for an externally supplied fitness measure. Genetic programs have been used for robot planning, automatic programming and pattern recognition. One use was the artificial ant problem of generating a finite state automaton to allow the ant to follow a winding and irregular trail with gaps (Santa Fe trail) using a sensor that can see only the adjacent cell in the direction in which it faces. Complex emergent behaviours are genetically evolved by using a computer program for each individual ant in a colony to generate a maximally optimal program for the efficient transport of food via pheronome trails. Essentially the co-evolution process models the biological arms race process.

Genetic programming uses high-level computer programs such as Lisp, Fortran, C, etc (typically Lisp) [Koza 1995]. Computer programs are sequences of function operations applied to arguments. Compilers translate programs into parse trees initially and then into assembly code. Thus any computer program may be represented as a rooted point-labelled tree with ordered branches. Genetic programming extends the genetic algorithm technique whereby each individual in the population is a computer program. The search space to be explored is the space of all possible computer programs composed of functions and terminals. To apply genetic programs certain properties need to be defined: set of terminals (inputs), set of functions (S expressions), fitness measure, parameters for run control and criteria for run termination. The functions in particular include add, subtract, multiply, divide, sine, cosine, etc. Such computer programs are bred to find the computer program that solves the problem. An initial population of computer programs of architectural diversity is randomly generated. The fitness measure defines the problem to be solved – it may be error measure, time to solution measure, correlation, classification, convolution, multiobjective function, output data sets, etc. Parental programs are of different sizes and shapes and offspring programs are also of different sizes and shapes than their parents. They are created by swapping of entire subtrees, subroutines, modules, etc. This sexual cross-over operator yields syntactically valid offspring. Based on the fitness function for the problem, better solutions are evolved over multiple generations. Hierarchical structures are generated through re-use and parametrisation through subroutines. The hierarchical structure comprises a main program and one or more re-usable, hierarchically called subprograms (automatically defined functions). Each multi-part program in the population contains one or more function-defining branches and one or more main result-producing branches. The main program calls one or more automatically defined function. A function-defining branch can call other automatically defined functions. The automatically defined function provides the basis for hierarchical scalability. Typically, an initial population of 500-10,000 computer programs will converge on a solution in 50 or so generations. The solutions they evolve defy systematic investigation due to their lack of structure. Genetic programming is particularly useful for NP-hard problems such as the travelling salesman problem for which there are n! routes for n cities. The chief problem is computational processing time.

There are three steps to genetic programming:

(i) Randomly create an initial population of computer programs

(ii) Iteratively perform the follwing steps for each generation until the termination criteria have been statisfied:
  (a) Assign fitness value to each program using fitness measure
  (b) Create new population of programs by applying three genetic operations with probability based on fitness:
    i. Reproduce individual by copying into new population
    ii. Create two new programs from two existing programs by genetic recombination of subtrees (cross-over)
    iii. Create new program from existing parent by random mutation

(iii) Find best-so-far computer program

Genetic programs attempt to map the labelled trees of genetic programs with cyclic electric circuit graphs. The circuit constructing tree makes the link. The technique has evolved low pass analogue filters similar to the Butterworth and Chebyshev filters. Genetic programs are generally limited to a small number of generations and are suited to essentially optimisation problems.

There have been attempts to unify the classifier system with genetic programming – s-classifiers which are expressed as Lisp s-expressions with a discovery component based on genetic programming. Traditional classifiers can only represent AND and NOT so that a generalisation involving OR would require at least two classifiers. However, s-expressions allow the use of OR within a single classifier.

Appendix C: Artificial Intelligence

An autonomous agent senses its environment and acts according to its sensory data in pursuit of its own goals. Biological brains are control systems that provide the function of intelligent autonomous behaviour. Goals include global goals, temporary sub-goals and continual goals (drives). A goal is to be differentiated from a belief: a goal is a representation for generating behaviour that alters the world to conform to it, whereas a belief is a representation that perceptual and reasoning processes alter to conform to the world. In addition, emotions, attitudes and motivations must be included to realistically emulate intelligent behaviour. Emotions are dispositions to certain types of behaviour as a means to allocate limited resources. Emotions add urgency and priorities associated with motives (needs) to aid conflict resolution – they act as context-sensitive filters. Emotions are states produced by motives and beliefs. Motives may be insistent (power to interrupt), importance (likelihood of adoption), urgent (limited window of opportunity), intense (energy expended in its pursuit). Irrationality is an inevitable byproduct of emotions in that they are fast reacting, resource limited interrupt filters. Failure of achievement generates pain while fulfilment generates pleasure. This brings in the problem of conflict resolution and competition for resources – purposefulness is a major characteristic of autonomous systems. Motives are essential in action selection.

SYMBOLIC SYSTEMS

The physical symbol hypothesis states that general intelligence (including human) is realised by a symbolic system – indeed, that symbol processing is a necessary and sufficient means to general intelligence. Such a symbol processing system may be represented using formal logic (eg. Prolog). Essentially, the physical symbol hypothesis is a corollary of the Church-Turing hypothesis. Symbolic systems are exemplified by expert systems which generally use production rules. For a planning system, the expert system begins at some initial state T_i and transforms into a final state T_f through a series of intermediate transition states. The initial state describes the current state of the world while the final state describes a goal state of the world. The intermediate states describe a trajectory. The production system comprises three components: a global database which stores contextual data (working memory) which represents the current state of the world; a set of production rules (long-term memory) which are transformation operators and have the form of condition-action rules (if <condition> is true, then perform <action>); and a control structure which selects relevant production rules based on which condition parts of the production rules are matched and selected according to a conflict resolution strategy to ensure that consistent productions are activated. Conflict resolution can be minimised by making the production rules highly specific but there will always be a need for general rules to cope with generalised tasks. Firing of production rules alters the state of working memory through the performance of an action described by the action part of the production rule. The production system essentially performs a search from the current to the goal state. A variation on this theme is the blackboard in which the working memory is shared by a number of independent sets of production rules (knowledge bases). SOAR is an exemplar of this symbolic processing paradigm in which its knowledge of the task environment is encoded symbolically as production rules. It uses symbol processing to transform its current state into the goal state by searching its problem space. It attempts to search for those transformations (subgoals) which minimise the distance to the goal (means end analysis). At each recursion, it matches its condition parts of its production rules with contextual data in working memory which define which production rules are activated. Similarly, the action parts of the triggered production rules alter the current state of the world encoded in working memory. Sometimes, the recursion process fails and an impasse results prior to reaching the goal state. A subgoal is automatically generated which must be solved before continuing to the final goal state. A new problem space must be generated to solve this subgoal. Such subgoals can be generated recursively and hierarchically and stored in a stack to reach its final goal. SOAR also implements a single learning mechanism – chunking – whereby a single production rule is generated representing the solution to the impasse, effectively encapsulating the subgoal search. Any future encounter with the impasse is thus solved using the production rule which encapsulates the subgoal procedure. Recent research attempts have been pursuing Robo-SOAR which interfaces SOAR with a vision system and a robotic manipulator to a simple "blocks" world.

Alternative forms of data structure than production rules include schema. Schema theory is based on Piaget's theory of child development of mental representations. These mental representations must be constructed afresh every time they are used. Children develop mental representations initially as mere sensory impressions and motor actions. Subsequently, they learn to associate some motor actions with resultant sensations. From this, the notion of physical object with a permanence beyond physical sensation is constructed. So, a model of the world as objects is built up. This is the basis of the schema mechanism. The schema controls the body which interacts with a world model, and this world model provides the framework for the organisation of knowledge. This knowledge is used to select actions to pursue goals. There are three types of data structure: items which are object states corresponding to sensory inputs, actions which are motor output sequences that cause state changes in the environment, and schemas which determine the effects of actions on environmental states. A schema form the central representation which comprises a context (a set of sensory items), an action and a result (a set of sensory items resultant from the action). It specifies that given a context, a specified action will generate a specific result. Schemas can be instantiated according to a probability modelling uncertainty. Schemas are cross-connected such that the results of one determine the context for the next - a plan is a set of schemas sequenced and coordinated to produce a given result. New schemas can be built from empty schemas. A variant on the schema is the script which can represent contexts and typical sequences of events, eg. restaurant situation. Scripts are data structures which include input conditions, roles, props, scenes, etc.

The pandemonium model of the mind is built on demons which are procedural rules (agents) which respond to specific stimuli and identify objects [Selfridge 1959]. Each demon may be implemented by a finite state machine or a production system. Populations of these agents are activated and interact through a blackboard, some generating external actions, others activating chains of demons, sometimes multiple demons. This is similar to Minsky's society of mind model. A demon excites other demons to which it is linked, the link being characterised by a strength which increases over time if activated multiple times. Rarely used links decay over time. The strength of a link is also influenced by motivational and emotional gain. Hierarchies of demons can be created. Demons that commonly appear together can be merged into a single demon (chunked).

Modal logics which introduce modal operators and involve the use of possible worlds. Kipke's modal logic adds two modal operators to first order logic: (necessarily) and ◊ (possibly): p is true if p is true in every world accessible from the current world, ◊p is true if p is true in at least one world accessible from the current world. The two operators are duals of each other in the same way that universal and existential quantifiers are: p⇔◊~p and ◊p⇔~ ~p. The axiom K (Kripke) (p⇒q)⇒(p⇒ q) is valid. In addition, if p is valid, then p is valid – this is the necessitation rule of inference (it is known that p). There are four axioms which define accessibility relations:

T: p⇒p (reflexive accessibility relation)
D: p⇒◊p (serial accessibility relation)
4: p⇒ p (transitive accessibility relation)

5: ◊p⇒ ◊p (Euclidean accessibility relation)
Axiom D is the non-contradictory axiom and may be re-written as Kp⇒~K~p which states that if p is known, then ~p is nt known. Axiom T is the knowledge axiom and distinguishes knowledge from belief in that knowledge is true belief. Axiom 4 is the positive introspection axiom which states that the agent is aware of what it knows. Axiom 5 is the negative introspection axiom which states that an agent is aware of what it does not know. The two axioms – the K and necessitation axioms – imply logical omniscience in that all valid formulae are known which conflicts with real resource-bounded systems. Meta-language introduces terms that denote formulae of another object language [Haas 1986]. The meta-language can represent a relationship between a meta-language term denoting an agent and an object language, eg. Bel(Alex "p"). However, meta-languages suffer from inconsistencies.

CYC is an expert system which attempts to implement common sense to overcome the brittleness of expert systems. It is a compendium of 3 million linked facts within a database stored in the form of logical clauses that assert truths about the world. However, the greater its knowledge, the more rapidly it learns.

Analogical learning is a high level perceptual process, eg. Hofstadter and Mitchell's Copycat. This is premised on the notion that perception results emerges from the activity of many independent but parallel processes. These independent processes (codelets) rely on an associative network of knowledge bases. Knowledge is comprised of fluid or fuzzy concepts. Copycat comprises an associative network of concepts and relational links (such as successor or predecessor links) between them (long term memory or slipnet) in which analogy emerges by spreading activation. The working memory is where perceptual information is input to the system. The population of codelets are simple demon processes which impose structure to working memory data when activated probabilistically.

There is little doubt that emotions are essential components to human cognition – they assign prioritorised values to behaviour selection and have important social functions. Reinforcement learning uses emotions to provide positive or negative guidance. Emotional selection is particularly important for agents with multiple goals and limited resources especially in dealing with new and unexpected situations. Lazarus (1991) takes the view that cognition is a necessary component to emotion and indeed is the causative factor in emotion. Emotion requires cognitive appraisal (harmful or beneficial) in order assess emotional quality (positive or negative) to situations and events and are dependent on the recent emotional history. Emotion – specifically, E={happiness, sadness, fear and anger} (only happiness is a positive emotion) - as an event detection mechanism has been investigated using robots with three primitive behaviours – obstacle avoidance, light seeking and wall following [Gadanho & Hallam 1999].

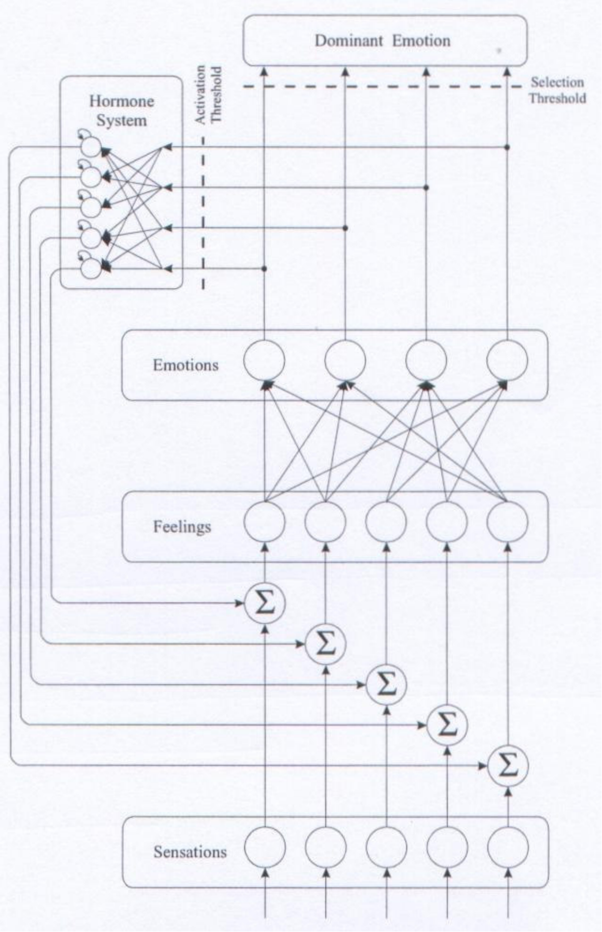


Fig C-1 Emotions model [from Gadanho & Hallam 1999]

Motivations which are based on internal state – F={hunger (depletion of energy), energy consumption (high energy availability), pain (obstacle collision), restlessness (encourages movement), temperature (based on motor usage), smell (to detect energy sources), proximity (obstacle avoidance), warmth (dependent on incident light intensity)} - determine emotional intensities. An active emotion influences the body through a hormone system. The hormone system provides competition between emotions for control of the body's state. The dependence of emotions on emotional history as well as sensory data prevent rapid changes of emotional state. A robot is happy when the current situation indicates smell of food, consumption of food, and high motor usage. If the robot has low energy and is not acquiring energy is sad. If the robot bumps into obstacles then pain will make it fearful. If the robot is in the same place for too long it will get restless and make it angry. An associative memory emulates reinforcement learning which outputs to the behaviour selection module. The intensity I_e of emotion e is given by:

$$I_e(t) = V\left(B + \sum_{m \in M} C_f I_f\right)$$ where M={list of motivations}

$$V(x) = \begin{cases} b- & \text{if } x<b \\ b+ & \text{if } x>b \\ x & \text{otherwise} \end{cases}$$

$$I_f(t) = V\left(C_h H_f + S_f\right)$$

C_f=hormone coefficient parameter
S_f=sensation derived from sensory values
$H_f=0$ if $n=1$
$= \alpha H_f + (1-\alpha) A_f$ if $n>1$
=hormone system
$A_f = \sum_{e \in E} C_f I_e$
$\alpha=\alpha_{up}$ if $|A_f|>|H_f|$ (attack)
α_{dn} otherwise (decay)
B=bias
C_f=coupling coefficient between emotions e and feelings f

CONNECTIONIST SYSTEMS

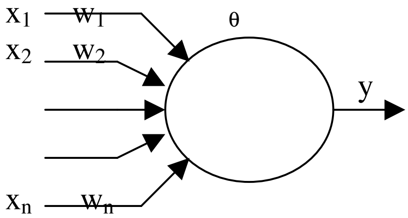
The problem with symbolic systems is that they suffer from the frame problem and cannot reason non-monotonically. The frame problem is based on determining which propositions remain true when actions are performed on the world which alter aspects of that world. The frame problem requires the addition of constraints which causes a computational explosion in complexity – it is an NP hard problem. Furthermore, symbols are manipulated without reference to their semantic meaning. Human reaction time (and by inference, characteristic cognitive relaxation time) is ~500 ms. Neural firing processes occur with a time constant of ~5 ms, so human reactions are physiologically constrained to ~100 serial neural firings (Feldman's 100 step rule). This limit to serial processing implies the need for highly parallel processing within neural structures of the brain. Rather than symbol processing, intelligence may be the result of pattern matching – this view is reinforced by the differences in human and machine approaches to solving chess problems. Pattern matching requires a large amount of knowledge of board positions while symbol processing requires brute force searches and look ahead of chess moves. There are five stages of learning of motor skills:

(i) a novice uses rules in a context-free manner
(ii) a beginner begins to use situational cues to apply rules
(iii) a competent actively examines and selects only situational cues that are relevant to the goal
(iv) a proficient selects only relevant cues without examination but by recognition
(v) an expert automatically reacts to recognised relevant cues

Connectionism adopts the parallel distributed processing of artificial neural networks to perform sub-symbolic processing at an abstraction below that of the symbol but above that of the individual neuron, ie. at the level of neuronal groups. There is no stored program and all processing is determined by local information. Neural nets suggest that neural structures of the brain generate intelligence through the interactions of large numbers of simple interconnected processor units. The human brain comprises $\sim10^{11}$ neurons, each connected to $\sim10^{4}$ other neurons. Each neuron performs a relatively simple function (modelled as switching in artificial neurons). Artificial neural networks emulate a much simplified model of the brain architecture. Biological neurons comprise of dendrites, a soma and an axon. Dendritic processes which receive excitatory and inhibitory inputs from other neurons. Within the axon, a voltage is generated in response to each dendritic input which are summed across all dendrites. If this sum exceeds a threshold, an output voltage is transmitted down the axon and transmitted as the output to the dendrites of other neurons. The connection between the axon of one neuron and the dendrites of another neuron is composed of a synaptic cleft across which chemical neurotransmitters diffuse from their location in the synaptic vesicles of the axon. The dendrites of the receiving neuron then generate an input signal in the postsynaptic neuron. Artificial neurons are modelled as a linear summing threshold unit. The simplest model is the McCulloch-Pitts neuron which is a digital model:

$$y(t+1)=1 \text{ if } \sum_i w_i x_i(t) \geq \theta$$

$$= 0 \text{ otherwise}$$



Inputs from the presynaptic neurons are binary in value (+1 for excitatory and –1 for inhibitory inputs). The synaptic efficiency of the axon-dendrite connection is modelled as synaptic weights w_i. The neural threshold is modelled as the minimum voltage θ required to fire the neuron. If the sum of weighted inputs (modelling the accumulated voltage inputs) exceeds the threshold, the neuron generates an output of 0 or ±1. In fact, real neuron outputs are more properly encoded as the firing frequency rather than firing amplitude. This simplified model takes no account of neural cellular processes such as ion channel function, etc. The McCulloch-Pitts neuron can model an OR gate (if either input is 1, the output is 1, otherwise the output is 0), an AND gate (if both inputs are 1, the output is 1, otherwise the output is 0), and a NOT gate (if the input is 1, the output is 0 and vice versa).

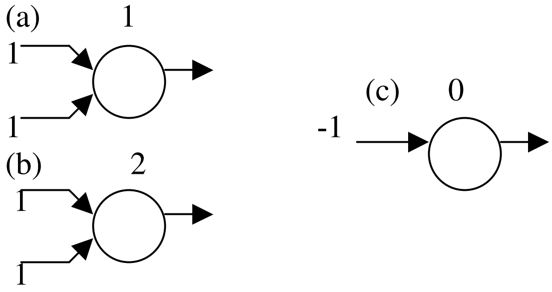


Fig C-1 (a) OR gate (b) AND gate (c) NOT gate

Hence, the formal neural network is computationally universal which as a Turing machine can model any algorithm through networks of Boolean neurons. The more complex XOR gate (if only one input is 1, the output is 1, otherwise the input is 0) however cannot be modelled by the simple formal neuron. It requires the addition of a hidden layer between the input and output layers:

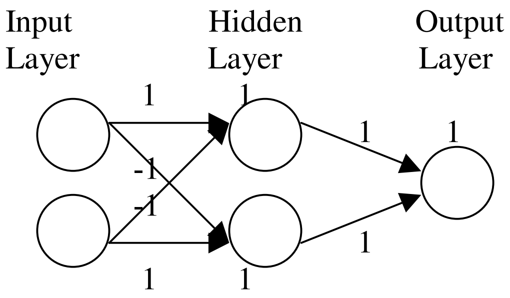


Fig C-2 XOR network

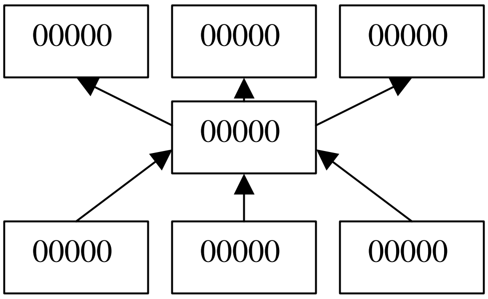
This is a five-unit layered feedforward network. The Rummelhart-McClelland neural network is a continuous input/output feedback network. The neurons are continuous in allowing analogue real rather than discrete integer values. Such fully-connected networks have been used for classification tasks such as the recognition of letters and words. The network configuration (short-term memory) is defined by its pattern of activation at a given time while the connection weight pattern (weight matrix) defines the network's long-term memory. The weight matrix for the XOR network is thus:

$$w_{ij} = \begin{pmatrix} 0 & 0 & 1 & -1 & 0 \\ 0 & 0 & -1 & 1 & 0 \\ 0 & 0 & 0 & 0 & 1 \\ 0 & 0 & 0 & 0 & 1 \\ 0 & 0 & 0 & 0 & 0 \end{pmatrix}$$

The weight matrix may be altered to define its response to a given set of inputs, ie. it learns by adjusting the connection weights. Backpropagation is the commonest form of supervised learning in a layered feedforward network whereby responses are compared with the desired output and the weights are adjusted to minimise the error. The network is trained on input-output example pairs. The error is propagated back through the network to modify the weights to reduce this error. For all the exemplars, the errors define an error surface in multi-dimensional n x n weight space where n=number of neurons. Backpropagation works by gradient descent on the error surface. Reinforcement learning provides a numerical cost function value computed over a sequence of trials to adjust the weights to minimise the cost function. Hebbian learning increases the connection weight between neurons that fire simultaneously. Unsupervised learning involves self-organisation whereby weights are adjusted in response to the inputs. The strongest outputs generated for a given input are strengthened while those that yield weak response are further weakened. This provides the basis for categorisation of the inputs.

Information can be stored locally or globally. In a local representation, each unit represents a single discrete object or hypothesis or symbol. This type of neural network processes symbols as patterns of activity rather than by inference rules. In a global representation, each unit contributes to a representation of a concept, and conversely, each unit may contribute to many concept representations. In this case, information is stored in a distributed pattern as a content addressable memory. N neurons can codify 2^N different patterns of activity corresponding to different concepts. The feature representation has individual objects represented distributively as patterns of activity over finite sets of neurons – individual neurons represent specific features that collectively represent the object. This provides the basis for learning categorisation and generalisation. Indeed, artificial neural networks are particularly effective at pattern recognition tasks, predictive signal processing and optimisation tasks. Global states emerge from the connectivity of the neurons through local interactions.

Pollack's recursive auto-associative memory (RAAM) is an input-output association memory which associates each input pattern with itself as the output pattern recursively. Consider three sets of five-input units, one set of five hidden units, and three sets of five-output inputs:



Each input unit of each input set is connected to each hidden unit, and each hidden unit is connected to each output unit. The backpropagation algorithm trains the RAAM so that its output pattern is identical to its input pattern. A coded version of the input layer is generated in the hidden layer which produces that same input pattern as the output. The input and hidden layers act as encoders while the hidden and output layers act as decoders for data compression. This may be used recursively to store arbitrarily long input sequences into a fixed length representation scheme. Such devices have been used to encode words and phrases (symbolic) and trained to yield a desired response given a training set of input-output pairs. This allows the processing of discrete sequences of symbols in a distributed network [Chalmers 1990]. Connectionist systems have a complex distributed microstructure of microfeatures which allows representation without rules but which can retain syntactic structure of symbols.

GENETIC ALGORITHMS

Genetic algorithms are search algorithms based on a model of biological evolution. Genetic algorithms begin with an initial population of states on which selection is iteratively applied to generate evolution of the population towards a solution to the problem. The processes of reproduction, mutation and selection are applied to each generation iteratively. Essentially, the state space is searched in parallel. Typically, the genetic algorithm has the form of a bit string encoding a hypothesis or solution, or alternatively, the genotype may be more complex, eg. hierarchical structure. The alphabet of the genetic code is binary A={0,1,*}. The following sequence is applied:

(i) initialise a population of genes with random alleles
(ii) assess the fitness of each member of the population according to a fitness function
(iii) select the fittest members for reproduction in proportion to their fitness
(iv) randomly sexually combine these fittest members with each other through cross-over with a randomly generated cross-over point(s)
(v) add a low level of mutation by randomly flipping alleles
(vi) insert these new members into the population either replacing the parent members or replacing least fit members
(vii) goto (ii)

Genetic algorithms may be used in artificial neural networks to search for the optimal weights of the network. This mixture of evolution and learning represents one approach to hybrid systems. Similarly, the classifier system offers the possibility of combining production systems and genetic algorithms. Classifier systems use genetic algorithms to evolve condition-action production rules, particularly for animats. Each classifier comprises 0, 1 and *. Each classifier comprises a taxon (condition) to detect feature vectors (typically binary), an action which can move the agent into one of 8 discrete directions, and a strength which numerically defines the classifier's value to the animat. The agent starts with a population of random classifiers which evolves over time. Learning occurs by several means. Reinforcement of the classifier strength increases the probability of a classifier being activated. The bucket brigade algorithm copes with sequences of actions such that strength values are passed back along the sequence generating the desired culminated action. Classifiers pay a portion of their strengths to previously active classifiers. The bucket brigade algorithm operates thus:

(i) remove a fraction of the strength of each classifier in the set of matching classifiers [A(t)] yielding the same final action A (t)
(ii) distribute this fraction among classifiers in the previous matching classifier list [A(t-1)]
(iii) perform action A(t)
(iv) if reward is received, distribute it among classifiers [A(t)]

Activation of a classifier reduces its strength by paying off previously activated classifiers according to its current strength. On receipt of the reward signal from the environment, this is redistributed among the chain of classifiers that generate it. Genetic operators generate new classifiers. A classifier is selected for genetic operation with probability in proportion to its strength. Cloning simulates asexual reproduction in generating an identical classifier. Cross-over of two classifiers simulates sexual reproduction with randomly generated cut points and interchanges genetic material with a common action from both parents. If the parents alleles were the same, this is passed onto the child, otherwise a * is substituted. To maintain a fixed population, classifiers are deleted at random or in proportion to the reciprocal of strength (removal of weakest classifiers causes a loss of genetic diversity). If the matching set of classifiers is empty, ie. there is no match of classifiers to the detected feature vector, a new matching classifier is generated (with some substituted * alleles) which has a random action.

SITUATED COGNITION

Artificial life-based agents systems are built on the animat concept such that intelligent behaviour is based on previous successful behaviour in a multitude of situations, ie. learning through reward/punishment awarded by the environment. To achieve this, it must survive in a hostile environment. Biological animals have been shaped by evolution by natural selection – the environment provides the basis for natural selection. Animats must filter sensory signals to focus on the small number of relevant signal and ignore the much larger set of irrelevant signals. Furthermore, actions imposed on the environment by the agent will alter the sensory signals. Animals act to maximise the positive reward signals and minimise the negative punishment signals. The basic problem is to associate sensory signals with the required actions according to those constraints – an optimisation problem. The animat model however typically inhabits a rectangular grid as its environment. It receives signals from each of its 8 neighbouring positions. Typical tasks include the ability to differentiate between obstacles or prey and food. Each feature detector gives a binary response (1 or 0 depending on presence or absence). Furthermore, it yields an 8-bit direction vector. The animat can move one square at a time in any of its 8 digital directions. Moving to a location with food results in the food being eaten and a reward signal. Moving to a location with an obstacle generates a punishment signal which reduces the animat's health. When the health of the animat drops below a certain threshold, it dies. Evidently, the number of objects that can be classified depends on the detector – d detectors can detect 2^d types of objects. The animat may utilise a population of classifiers following an algorithm:

(i) compute feature detector vector D
(ii) find matching set M of classifiers in population P that match detector D
(iii) select classifier C from M with probability dependent on strength
(iv) perform action A defined by classifier C
(v) goto (i)

Measurement of the distance to food allows favouring short paths. The selection of a move is based on the probability proportional to the ratio of its strength-to-distance. An additional tax is imposed when activated classifiers yield conflicting actions, the tax acting as a lateral inhibition. More complex environments can include carnivorous predators which seek out agents as prey with long distance detectors. Similarly, the use of populations of agents provides a social dimension. Agents or carnivores may reproduce when sufficient energy levels are stored, so allowing for variable population sizes. The population of agents evolves and each agent learns. Each agent selects actions based on its neural network control system which also provides its mechanism for learning (by backpropagation supervised by a reward generator after each action) over its lifetime. The genetic code for each agent encodes the initial weights of its neural network. There is no explicit fitness function – the environment acts as an implicit fitness function [Ackley & Littman 1992]. The use of both learning and evolution provides the basis for the Baldwin effect such that learned features gradually become inherited.

The environments adopted in artificial life research are very simple two dimensional arrays of cells and not representative of real world environments – the process of classification requires sophisticated perception. Furthermore, representations of objects are actively constructed and categorised by the agent with respect to its behaviour and survival rather than as externally existent labelled objective structures.

The nouvelle AI paradigm is based on the physical grounding hypothesis which states that intelligence requires representations to be grounded in the physical world – symbols are not so grounded. The world is its own best model as it is updated in real time and contains all levels of detail and abstraction. This behaviour-based approach decomposes intelligent behaviour into individual behaviour-generating modules. In order to ground the system, each behaviour must be connected to the physical world by sensors and actuators. Higher levels of abstraction are built from concrete objects in the world as measured by sensors. The subsumption architecture provides a series of incremental layers of behaviours. Each behaviour provides a tight linkage between sensors and actuators providing the physical grounding. Each behaviour module provides a basic prototypical competence. For a typical mobile robot, level 0 specifies obstacle avoidance, level 1 specifies wandering exploration, and level 2 specifies attraction to targets. Each behaviour module may be implemented as an augmented finite state machine. The finite state machine is characterised by a finite input and output alphabet, a finite set of states, and a transition function. The transition function transforms the internal state and input into a different state and an output. The augmented finite state machine has in addition a number of registers to store the input data and a set of timers which prohibit state changes and outputs whilst switched on for a given duration. It can perform if-then-else functions. The suppression of behaviours allows for the disabling of behaviour modules by other active behaviour modules to provide conflict resolution. Higher level behaviours can suppress lower level behaviours (subsumption). There is no other communication between behaviours other than this subsumption process. The chief problem with behaviour-based control is that it does not appear to scale up to more sophisticated behaviours beyond a few layers of simple behaviours.

Basic behaviours (which may be modelled as finite state machines or production rules) may be invoked by specific environmental stimuli. They comprise of a precondition list, activation level, effect of action, an add-list and a delete-list for the blackboard (similar to classifiers). Hierarchical organisations of behavioural modules are inflexible. A dynamic distributed organisation provides greater flexibility. Similarly, links are defined with modifiable weights lending it to implementation through a symbolic connectionist system. The add-list may add a proposition to the blackboard which matches one of the preconditions of another module's precondition list, thereby activating it. The delete list provides an inhibitory function to behaviour modules. There may be multiple links between the same modules or different modules. The more preconditions that are applicable, the greater the activation of the behaviour module, so providing a mechanism for relevance to environmental situations. Multiple behaviour competence modules may interact to generate complex behaviours. Behaviour networks of distinct behaviours employ spreading activation to select behaviours with inputs from the environment and goals [Maes 1990]. Activation spreads from behaviour module to behaviour module along the links. Along successor links, one module strengthens those modules whose preconditions are fulfilled. Along predecessor links, one module strengthened other modules whose add-list fulfils its own preconditions. A module sends inhibition along a conflictor (inhibitory) link to modules which can delete any of its preconditions. The algorithm runs this:

(i) add activation from the environment and goals
(ii) spread activation forward and backward through the behaviour modules
(iii) implement decay to ensure that total activation energy constant
(iv) a behaviour module is activated if all its preconditions are satisfied and its activity level exceeds the threshold
(v) if a behaviour module fires, its activation energy is nullified and thresholds return to their default values
(vi) if no behaviour module fires, all thresholds are reduced by 10%

Due to constraints such as the unpredictability of the dynamic world and limited access to resources, behaviour selection is not optimal but must be satisficing. The autonomous agent must balance persistence (goal-orientation) and opportunism (reactive). The global threshold provides the basis for planning by reducing the influence of sensory inputs and motor actions. Varying the threshold allows flexibility in determining the tradeoff between planning and reactivity. Planning in behaviour networks is implemented by tracing a forward/backward path between goals and sequences of actions that satisfy the goals. Forward activation spreading promotes situation relevance while backward activation spreading favours goal planning. Activation spreads backwards from the goal to modules which define its preconditions and so through the network. However, there is no central planning facility employing symbol manipulation as the plan arises from the search tree generated by spreading activation.

Deictic (indexical-functional) representation does away with a fixed world model. Planning in the real world is a complex process that involves planning ahead through simulation and improvisation as the plan proceeds. Full planning cannot be achieved due to the vast number of unpredictable possibilities and incomplete information. Most planning activity is enabled by simple mechanisms that exploit regularities in previously experienced situations similar to the current one. However, there is no need for an explicit model of the world. Complex behaviours arise from the complexity of the environment. Pengo is a game played on a two-dimensional maze of ice blocks. The player navigates a penguin icon with a joystick. The penguin is chased by bees which try to kill the penguin. Both penguin and bees can kick ice blocks to make them slide which kill bees and penguins on contact. Pengi is a software agent which plays Pengo but follows no rigid plan but reacts to immediate situations. Pengi has a set of goals and a set of skills, and follows routines opportunistically – patterns on interaction between the agent and its world. These routines are real-time rule-based responses which are situation independent anf goal independent. All objects and actions are defined relative to the agent itself – these entities are embedded with respect to some aspect of the agent's current situation. Relevant aspects of these entities are the properties of the situation that are relevant to the current goals and are used to select the next action. These indexical-functional aspects are functional in terms of their functionality in relation to the current situation. Aspects are indexical in that they are defined as the current situation relative to the agent's goals. Hence, all irrelevant perceptual data is filtered out. Objects are defined only in terms of relevance to the agent's task at hand. The Pengi architecture was based on a set of peripheral systems for perceptual input and effector output interfacing (including a sophisticated vision processor), and a simple central system without complex representations. The vision processor maintains two-way interaction with the central system such that the central system provides expectations of aspects to the vision processor. The central system comprises a combinatorial network of Boolean functions (a neural network would work just as effectively) which determines which actions are appropriate to the situation. As the world changes due to the generation of actions, so the perceptual inputs change and continually drive the selection of actions without any form of memory. Each action is selected according to its plausibility for the current situation, of which there may be several choices of action. The most appropriate action emerges depending on the activation of the central system.

Appendix D: Architecture of the Human Brain

The brain is essentially a sensor-effector control system. However, brains are not absolutely essential for complex behaviours: box jellyfish are fast, active predators with complex predatory behaviours which sleep at night unlike most primitive creatures. They have 24 eyes arranged in clusters of 6 (four simple light-sensitive pits and two colour camera eyes with lenses, retinas and corneas), one of each side of their cuboidal bodies. Although it possesses sensory nerve cells for processing visual data, it has no brain for integrating sensory information into behaviour.

Most data concerning human brain function cames from cerebral thromobis (stroke) or other brain damage aphasias [Geschwind 1979]. The primary purpose of the brain is to analyse sensory data and control movement, ie. an input-output processing device. Sensory neurons transmit information from the periphery to the central nervous system (CNS) while motor neurons transmit information from the central nervous system (CNS) to the effectors. Interneurons process the information in the central nervous system between the sensory and motor systems of the body. The nervous system is divided into the central and peripheral systems. The somatic part of the CNS is concerned with control of the voluntary muscles while the autonomic part is concerned with the control of the viscera, vessels and internal organs.

The brain is composed of an interconnected system of 10^{11} neurons of white and grey matter which act as complex analogue processor units and each is connected to ~10^3 other neurons, ie. ~10^{14} synaptic connections [Hubel 1979, Stevens 1985]. White matter differs from grey matter in possessing myelin sheath to aid nerve conduction. There are two types of neuron – interneurons and output neurons. Interneurons perform processing while output neurons interface to muscles or sensory organs. A typical motor neuron synapses with a very large number of axons from ~10^3-10^5 interneurons typically. A somatic motor fibre terminates on sketal muscle while autonomic motor fibres terminate on cardiac muscle, smooth muscle and glands. The inside and outside of the neuronal cell has different concentrations of charged ions which creates a potential difference across the plasma membrane [Catherall 1984].

The ecological approach to human cognition suggests that all perception is rooted in action, so that cognition, and the cerebral cortex in particular, serves the add refinement to motor control in providing longer-term goals for greater adaptation to the environment and ultimately better prospects for survival. The cerebral cortex is highly irregular and complex but it possesses a fundamental basic architecture befitting its associative memory role [Marr 1970]. It has six layers of cells (layer I at the surface to layer VI deep within the cortex). The principle cell type in the neocortex are pyramidal cells. The somatosensory cortex has a distinct layer IV as it receives sensory information while the motor cortex receives little sensory input so its layer IV is indistinct. However, the motor cortex which outputs information has a prominent layer V. The motor cortex possesses neurons whose activity is tuned directionally such that the frequency of discharge is a linear function of direction cosines of the motion vector – they sre distributed uniformly in 3D space [Georgopoulos 1995]. The corticospinal tract originates as pyramidal axons of layer V of the primary motor cortex. The motor cortex undergoes reorganisation during the acquisition of skilled motor tasks. All motor behaviour is channelled through different levels of the ventral horn of the spinal cord which contain α-motor neurons which innervates muscle contraction of skeletal muscles, most motor neurons occurring in the cervical and lumbar regions to the limbs (there are 8 cervical, 12 thoracic, 5 lumbar, 5 sacral and 1 coccygeal nerves). Motor neurons in the ventral horn follow a topographical relationship similar to that in the somatosensory afferents. Spinal reflexes derive directly from proprioceptive muscle spindles which synapse within the spinal cord on alpha motor neurons that innervate the muscle – this is the myotatic stretch reflex implemented by one afferent neuron conncted to a muscle spindle to detect muscular stretch and one efferent motor neuron to generate muscular contraction. Alpha motor neurons stimulate gamma motor neurons to innervate muscle spindle to control movement through muscle stretch feedback. Golgi tendon organs feedback muscle tension data. There are three major tracts – ventromedial, dorsolateral, and lateral corticospinal tracts, the latter originating from the primary motor cortex and parietal cortex (in higher mammals only). The primary motor cortex is located in the pre-central gyrus which exhibits a topographical organisation with medial neurons activating lower limbs and lateral neurons activating upper limbs. The motor cortex initiates movement. Posterior parietal cortex integrates sensory information and projects into the prefrontal cortex and motor cortex in planning movements. The striatum (comprising the caudate and putamen) receives input from all parts of the neocortex, thalamus (which receives input from the cerebellum, pallidum and temperature and pain information from the spinal cord), substantia nigra, basolateral amygdala and hippocampus. It projects to the globus pallidus and substantia nigra.

Neurons with 5 ms firing rates allow us to solve complex problems in the conceptual domain in 500 ms timescales, ie. 100 sequential timesteps due to its high interconnectivity [Feldman 1989]. A compact representation assumes a "grandmother" cell with one concept per neuron which may be manipulated through logical ANDs. Topographical maps in areas such as the motor and somatosensory cortex, columnar organisation of the visual cortex favour this model. A coarse holographic or Fourier representation stores concepts as patterns of activity and requires a thresholded sum of activity but such shared representation suffers from cross-talk. The neurons perform input-output correlations through linear thresholding with robustness to noise (eg. Hebb's rule). To minimise cross-talk, each pattern should activate a number of unit proportional to the logarithm of the total number of units, eg. a network of 10^6 neurons should use an encoding of around 20 units per concept. The human brain is most likely a compromise between these two representations as redundant storage is required for robustness. In fact, a single small stimulus can generate activity in significantly large regions of the brain. However, there are specialised regions of the brain as complete connectivity is not physically possible. Symbols are mathematical objects that represent discrete entities in the real world and implementation of symbols and symbolic manipulation within neural networks is a thorny problem. Jaeger (1997) suggested that discrete, dynamical symbols correlate to identifiable motor action patterns within transient periodic and chaotic attractors similar to those found within artificial recurrent neural networks. Symbol manipulation is implemented through bifurcations which allows a trajectory to pass from one transient attractor to another, the bifurcation effectively isolating each symbol from each other in time.

THE NEURON

A neuron is a cell dedicated to the passage of electrical impulses through the body as the fundamental unit of the central nervous system. The concentration of ions inside the neuron is controlled by selective voltage-sensitive ion pumps in the plasma membrane. The insulatory membrane is constructed from phospholipids with high specific resistrivity and capacitance. The cell fluid is a highly conductive gel. The ion concentration of the fluid outside the cell is regulated by the kidneys (filtered blood). The different ion concentrations allow the system to act as a battery power supply to produce currents ~pA. The large central body of the neuron ~10μ in diameter, the soma, contains all the genetic and metabolic machinery for neuronal function such as ATP to drive the pumps. Dendrites are passive but complex branching structures extending out near the end of the neuron whose function is to receive inputs from other neurons and deliver outputs to other neurons via specialised synaptic contacts, ie. they receive afferent impulses. They may be represented as a series of capacitors and resistors. Axons are long, electrically active single output channels ~0.001-1.0m in length (however, interneurons lack axons but dendrites perform the output function), ie. they deliver efferent impulses. The neuron is a nonlinear integrating threshold device which sums excitatory and inhibitory inputs which produces a digital, all-or-nothing voltage pulse (action potential) which lasts ~1ms. The action potential threshold is determined by the membrane selectivity controlling the flow of Na+ and K+ ions across the membrane. When the potential on the presynaptic side of the neuron is increased, neurotransmitters are released thereby opening synaptic gates to allow charged ions to flow across the membrane. Output cells have graded analogue input with a digital all-or-nothing output. Interneurons however, have both graded analogue inputs and outputs – the graded potential output spreads out a short distance attenuating as it does so. All neural impulses have the same amplitude – neural information is frequency coded.

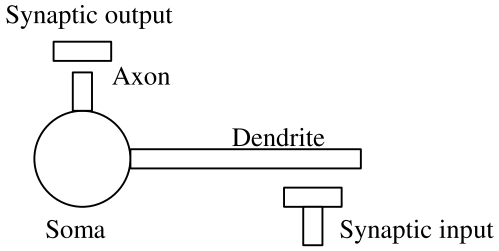


Fig D-1 Schematic of neuron

Glial cells occupy the space between neurons to provide structural support. Axons are often enclosed by insulating Schwann cells in multiple layers (myelin sheath) in ~1mm sections produced by the glial cells. Each myelin sheath section is separated by gaps called the nodes of Ranvier. Generally, different nerves contacting the same target cell tend to maintain their synapses on the target only if they commonly fire at the same time. Neurons are typically localised into groups (ganglia or nuclei), though in the cerebral cortex, they arearranged in sheets.

In the resting neuron, the concentration of Na+ is much higher outside the cell than inside by a factor of 10:1 due to leak channels in the plasma membrane providing permeability to K+ ions. The resting potential difference across the membraner is –70 mV with respect to the exterior of the neuron - this is maintained by specialised proteins of Na-K ATPase molecules in the membrane which provide energy to drive ions by creating a lower concentration of Na+ ions and lower concentration of K+ions outside the cell. The 5 nm thick cell membrane actively transports Na+ ions out of the cell and K+ ions into the cell at different rates such that a high concentration of K+ and low concentration of Na+ and are maintained within the cell. The opening of the ion gates lets Na+ ions into the cell and K+ out of the cell through their respective channels. This alters the transmembrane voltage creating a depolarising electrical signal – the action potential - down the nerve terminal. Gating is mediated by conformal changes in the channel proteins in the membrane pores which alter the membrane conduction by ~10^{-11} Ω^{-1}. In myelinated axons, the nerve pulse moves continuously down the axon activated by each successive set of Na+ channels which are distributed every 50-100μ through the cell body. Myelinated cells conduct pulses discontinuously as Na+ can only enter through the nodes of Ranvier gaps between each myelin sheath. This reduces the energy requirement for nerve impulses. The action potential is rapidly terminated by inactivation of Na+ channels and opening of the voltage-gated K+ channels. Long term potentiation (LTP) is a long lasting increase in synaptic efficiency following high frequency stimulation of afferent fibres, particularly in the hippocampus, and is implicated in the establishment of long-term memory through Hebbian mechanisms. It has been proposed however that LTP reflects a selective arousal mechanism under stress which alters the gain of environmental stimuli to increase associative learning of contiguous events as it typically lasts ~weeks which is much less than the typical residence time for long term memory, yet much longer than most forms of neuronal plasticity . [Shors & Matzel 1997].

THE SYNAPTIC JUNCTION

Electrical activity in presynaptic neurons trigger the release of neurotransmitters that diffuse across the synapse and act on receptor molecules in the postsynaptic neuron. The activated receptors generate responses in the postsynaptic neuron as membrane depolarisation. Chemical signals involve the transfer of molecular transmitters between the synaptic gaps between neurons. The presynaptic axonal terminal contains synaptic vessicles which hold ~10^4 chemical transmitter molecules – opening of the vessicle creates a temporary increase in transmitter concentration across the ~25 nm junction. The transmitter diffuses to the postsynaptic membrane of the adjoining dendrite and alters the postsynaptic membrane potential thereby varying the nerve pulse rate. Depolarisation of the presynaptic membrane by action potential opens the voltage-mediated Ca++ channels allowing the influx of Ca++ to trigger the release of chemical neurotransmitters from the synaptic vessicles. At the postsynaptic cell, ligand-gated ion channels determine the postsynaptic effect of the neurotransmitter. The transmitter is eliminated at the postsynaptic cell by enzyme degradation. Synaptic efficiency can be altered by providing a basis for memory, eg through posphorylation of ion channels at synapses such that the release of neurotransmitter stimulates the intracellular formation of cyclic AMP which activates the protein kinase. Over 200 types of chemical neurotransmitter have been identified, eg. acetylcholine which is the commonest excitatory transmitter, and GABA which is the commonest inhibitory transmitter. The transmitter appears to be localised to different regions of the brain [Iverson 1979]: dopamine (associated with emotions) characterises the mesencephalon and olfactory bulb extending into the forebrain and striatum; norepinephine (associated woith arousal) characterises the lower brainstem, the reticular formation and pons extending into the cerebellum, hypothalamus and forebrain; serotonin (associated with homeostasis) characterises the brain stem projecting into the hypothalamus and thalamus. Neuropeptides are chains of up to 40 amino acids present in interneurons and include ekaphalins and endorphins which exert significant global effects on brain activity even in minute quantities.

Learning alters the quantity of chemical transmitter release [Kandel & Schwartz 1982]. This is determined by the concentration of free Ca++ in the presynaptic terminals – Ca++ enables the synaptic vessicles to bind and release transmitters in the presynaptic terminal. Environmental stimuli cause long-term neural changes and alters the levels of RNA transcripts encoding neurotransmitters which in turn alters the synaptic function. Impulses actively alter gene expression and increase mRNA synthesis and neurotransmitter protein synthesis over the long term. Hence, neural plasticity is provided by altering tranismitter phenotypic expression in the nerve cell soma. Protein phosphorylation is mediated c=by cycluc AMP which alters the synaptic strength by increasing Ca++ flux into neurons. Cyclic AMP stimulates phosphorylation of membrane proteins which deactivate channels and slow reploarisation of the action potential allowing Ca++ influx. This allows more synaptic residues to release more transmitter. Low Ca++ concentrations induce irreversibloe increases in the number of transmitter binding sites in the hippocampus, amygdala, striatum and cerebral cortex (though not in the brain stem). The threshold level of postsynaptic activation required for modification is related to the voltage-dependent Ca++ influx. Ca++ activates neural proteinases that regulate the postsynaptic neurotransmitter binding sites. This activity is restricted to the telencephalon and limited to higher mammals. As this effect is temperature sensitive (with maximum at 35-40^{o}C), it cannot occur in fish or amphibians in temperatue zones.

ARCHITECTURE OF THE HUMAN BRAIN

The spinal cord is segmented. Spinal nerves of the brain connect to the spinal cord and through the dorsal (sensory) and ventral (motor) roots. The spinal nerves are connected to the spinal cord in pairs from upper to lower: 8 cervical nerves, 12 thoracic nerves, 5 lumbar nerves; 5 sacral nerves, and 1 coccygeal nerve:
C5 deltoid
C5/6 bicep
C6 brachio radialis/extensor corpi radialis
C7 tricep/extensor digitorum
C8 finger flexors
T1 small hand muscles
L1/2 fliopsoas
L2/3 adductors
L3/4 quadriceps
L4 tibialis anterior
L4/5 tibialis anterior
L5 extensor hallucis longus
L5/S1 peronei
S1 gastroenemius
In the spinal cord, information is processed by grey matter of the dorsal and ventral horns of each spinal nerve pair. The brainstem tegmentum is a continuation of the spinal cord and it includes the reticular formation, inferior olive nuclei and red nucleus – the somatosensory pathways pass through the tegmentum to the thalamus. The human brain is characterised by a distributed cooperative computational design with two specialised hemispheres and multiple specialised regions [Geschwind 1979]. The mammalian brain is broadly divided into the prosencephalon (forebrain), mesencephalon (midbrain) and rhombencephalon (hindbrain). The prosencephalon comprises left and right cerebral hemispheres (telencephalon) connected by the diencephalon. The frontal two-thirds comprises the hypothalamus, the other third being the thalamus. The telecephelon, composed of grey matter, is the largest part of the manmalian brain – its surface is covered in the cerebral cortex which is strongly convoluted giving a large surface area. During embryogenesis, the neural tube appears as three swellings of the primary brain vessicles representing these major components. The dorsal portion of the hindbrain the cerebellum appendage. The forebrain undergoes most subdivision and differentiation during embryogenesis including left-right pairing of the outer part of the cerebral hemispheres. The human brain comprises the brainstem (medulla, pons, midbrain), cerebellum, diencephalon and cerebral hemispheres. There are three main functional blocks to the brain providing its basic functions. The upper and lower parts of the brain stem and the reticular formation control general arousal levels and alertness, and regulates sleep. The reticular formation is evolutionarily ancient as attention is one of the most fundamental adaptive mechanisms. The reticular formation receives inputs from heterogeneous regions of the the brain and integrates a vast array of ascending and descending fibres and dispatches impulses to the spinal intermediate neurons and so to motor neurons. The second block at the rear of the

cortex performs analysis, coding and information storage. The third block is located in the frontal lobes which manipulates symbolic information and forms intentions and behavioural goals. Brain tissue is of two main types: grey matter and white matter [Nauta & Freitag 1979].

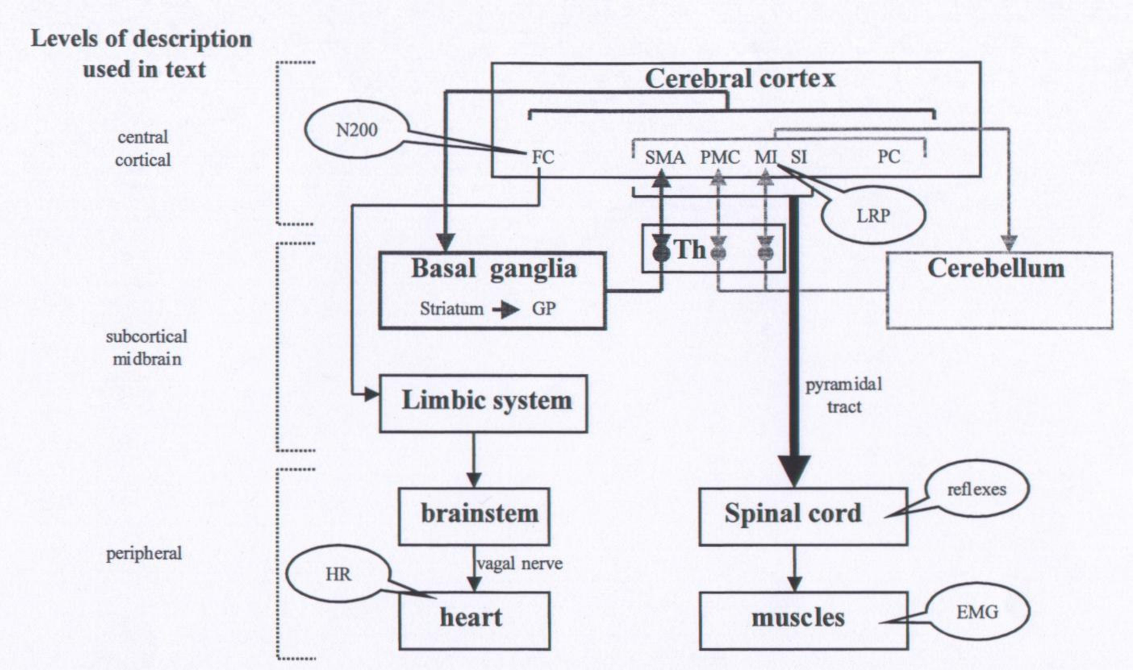


Fig D-2 Schematic diagram of major brain features

CEREBRAL CORTEX

Birds are the most behaviourally complex animals apart from primates and cetaceans. However, their cortex is relatively undeveloped while their forebrain regions – the Wulst and hyperstriatum – are expanded. In mammals, however, the cortical regions are expanded. The cerebral cortex contains pyramidal cells and inhibitory cells in the ratio of 4:1 forming two dimensional layers which are organised hierarchically. The cerebral cortex is around 2mm thick with a surface area of 2000 cm^2. Neurons in the network settle into dynamic clusters of cells that fire together and then disappear to reform elsewhere. The cerebral cortex is divided into several cytoarchitectural regions with distinct cellular and connectionist characteristics. Deep structures of the cerebral cortex are the basal ganglia. Grey matter consists of tight aggregations of neurons which comprise the surface of the cerebral cortex while white matter comprises mostly of nerve cell axons for long distance communication located deeper in the brain. The cerebral cortex is a 1.3-4.5 mm thick layer over the surface of the brain highly convoluted into folds (gyri) and furrows (sulci) with a strongly uniform and layered structure. It comprises of repeated modular hypercolumns ~200-300μ in diameter with six cortical layers. Radial fibres are interspersed between the columns. Axons make connections within the columns to form closed circuits. The cerebral cortex is mostly concerned with sensory and motor functions but only ~10^6 of the $3x10^{10}$ neurons are motor and sensory neurons. The majority are intermediate computational neurons of the association cortex which perform mapping of sensory neuron data to the motor neuron data – they provide the basis for comprehension of sensory data by mapping object-images by comprison with previous experience – lesions cause agnosia disorders. There are only a small fraction of monosynaptic reflex arcs where sensory and motor neurons are directly connected (primarily for balance). Sensory stimuli are translated into electrical signals by specialised transducers. In the muscle stretch receptor, the sensory nerve terminal is depolarised by stretching with a magnitude of depolarisation encoded in the rate of action potential firing. The cerebral cortex performs the final integration of neural data associated with the higher cognitive functions. Some fibres come from the thalamus and other from wide areas of the cortex. The prefrontal cortex receives many association fibres from all other regions of the cortex and connections from the medial nucleus of the thalamus. This is where the formation of intentions and plans, abstract inferences and causal reasoning occurs and does not perform any sensory or motor functions. The cerebral cortex with its sensory and motor areas have taken over many of the older deeper areas of the brain such as the brain stem. The cortex is characterised by intricately connected regions through numerous re-entrant pathways.

The primary sensory cortex areas have afferent connections from the sensory nuclei of the thalamus. At the back of the brain on the surface of the occipital lobes lies the primary visual cortex (area 17). In the photoreceptor, light causes conformatioin changes in rhodopsin molecules which cause the release of neurotransmitters. This causes the closure of Na+ channels and decreases its output of neurotransmitter. Visual data comes from the lateral geniculate nucleus of the thalamus. The primary auditory cortex resides in the temporal lobes while olfaction is focussed on the forward underside of the frontal lobes. Auditory hair cells and photoreceptors of the eye do not fire action potentials but signal the magnitude of the receptor potential to adjacent neurons via chemical synapses. The auditory cortex receives inputs from the medial geniculate nucleus of the thalamus. The angular gyrus between the visual and auditory cortex mediates between them. The olfactory system is the only system whose primary sensory neurons lie at the surface of the body without any transduction element – all other primary sensory neurons lie in ganglia under the surface of the body. Fibres project into the olfactory bulb which terminate in the olfactory cortex. The auditory system begins with the primary sensory neurons terminating on secondary sensory neurons of the cochlear nucleus in the hindbrain which convey fibres to the medial geniculate body of the thalamus which projects to the auditory cortex.

The primary motor cortex (area 4) stretches across the roof of the brain in front of the central sulcus of the cortex and initiates voluntary muscle movements. The motor cortex is responsible for voluntary motor control over the muscles of opposite sides of the body. It comprises large pyramidal cells with very long axons projecting towards the spinal cord. It receives inputs from other parts of the cortex, the cerebellum and the basal ganglia. The premotor cortex (area 6) lies in front of the motor cortex and coordinates and sequentially links units into complex motor activity. It has subcortical connections with the coordination nuclei of the thalamus through which it links to the cerebellum.

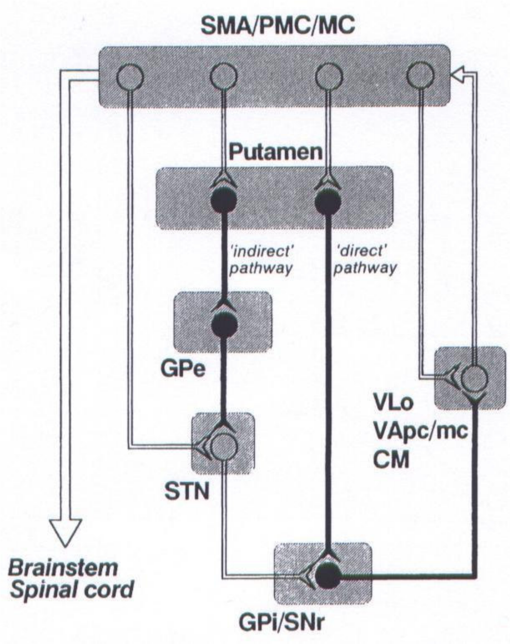
Motor neurons lie within the spinal cord, hindbrain and midbrain (none exist in the forebrain). These comprise the lower motor system for local motor control of different parts of the body. Within the hindbrain, motor neuron projections originate in the inner two-thirds of the hindbrain reticular formation. Within the midbrain, motor projections originate in the superior collicus and red nucleus – the superior collicus receives input from the optic nerve and cerebral cortex while the red nucleus receives input from the cerebellum and the motor cortex. All motor fibres descend into the spinal cord coveying commands originating from a wide region of the brain, especially the cerebral cortex. The superior collicus obtains inputs from the optic nerve and large regions of the cerebral cortex. The red nucleus obtains inputs from the cerebellum and the motor cortex.

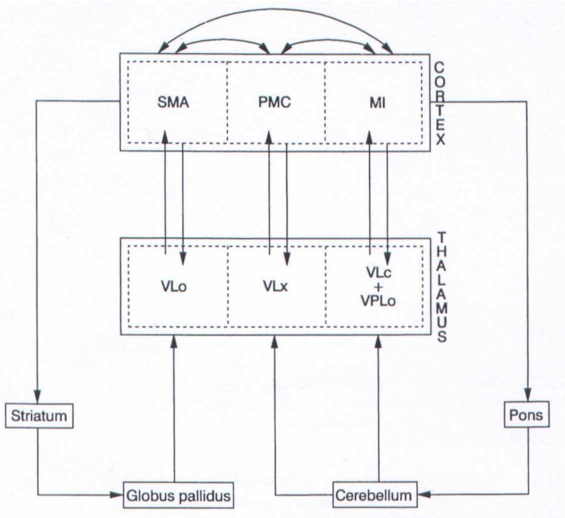
Behind the motor cortex lies the primary somatosensory cortex (area 3) which receives signals from the skin, bones, joints and muscles from all regions of the body via the ventral nucleus of the thalamus. It receives proprioceptive ffedback from the muscles and joints. Both of these cortical regions have regions which correspond to the parts of the body forming a cognitive map of the human body (homunculus map). The distortions in the homuniculi relate to the precision to which the body part is controlled. The motor cortex represents the body topographically from the bottom to to the top of the cortex: larynx, tongue, face, thumb, hand, forearm, arm, thorax, abdomen, thigh, calf, foot and perineum muscles – the areas for the hand, tongue and larynx are disproportionately large. The mapping between the body and cortex is distorted since the area of the cortex is reflected of the sensitivity and degree of fine control of that body part. The somatosensory cortex in the post-central gyrus processes a multitude of sensations from the body – touch, pain, pressure, temperature, and proprioception. These modalities are grouped in to thee distinct pathways in the spinal cord - discriminative touch pathways (touch, pressure and vibration) which cross high in the medulla, pain/temperature pathways which crosses low in the spinal cord, and proprioception pathways (muscle stretch, joint position, tendon tension, etc) which passes through the cerebellum and so does not cross. Sensation from sensory neurons are transmitted to the dorsal root ganglion outside the spinal cord which send axons up the spinal cord to synapse at the medulla. The gracile fasciculus tract carries information from the lower half of the body while the cuneate fasciculus carries information from the upper half. From the medulla, secondary afferents pass through the brainstem as the medial lemniscus through the pons to synapse in the thalamus and finally ascend to the somatosensory cortex.

The parietal cortex adjoining the somatosensory cortex is characterised by multiple pathways to other cortical areas. Spatial analysis for motion tracking is performed within the parieto-occipital areas of the cortex. Parietal cortex caudal and ventral to the primary parietal cortex are activated during imagination and the same parietal areas are involved during execution. The posterior parietal cortex may be the site where action representations are stored, integrating visual and somatosensory data and performing transformations from retinocentric object coordinates in egocentric coordinates. The hippocampus and prefrontal cortex are also implicated in spatial cognition for action, connected to the parietal cortex through reciprocal connections.

Each side of the motor and sensory cortex is concerned with controlling the opposite side of the body and these regions are in general symmetrical on each hemisphere. In vision, the right and left fields of view from each eye are projected through the optic chiasm where each optic nerve bifurcates on opposite hemispheres of the brain. A similar situation occurs with tactile information. However, the cerebral hemispheres are not completely symmetrical [Geschwind 1972, 1979; Gazzaniga 1989] – such asymmetry exists also in singbirds, monkeys and other mammals. Linguistic ability and expression resides mostly in the left cerebral hemisphere while the right cerebral hemisphere houses aptitudes for complex pattern recognition. The left hemisphere has an enlarged planum temporale which lies on the upper surface of the left temporal lobe within the sylvian fissure that runs along the left side of the brain. This incorporates Wernicke's area (between the auditory association cortex and angular gyrus) which provides linguistic competence. The angular gyrus around the temporal sulcus mediates between the visual and auditory cortex and is concerned with written comprehension. Wernicke's area requires input in auditory code so the angular gyrus converts visual information such as the written word into auditory form. All language inputs are processed in Wernicke's area at the posterior end of the superior temporal sulcus. It obtains inputs from the primary visual cortex (for reading and signing), from the auditory cortex (for speech), or from the somatosensory cortex (for braille). Lesions to Wernicke's area causes loss of sentence understanding but maintenance of grammatical fluency. Broca's area is located adjacent to the motor area for the face, tongue and larynx. All language outputs are derived from Broca's area to the motor cortex for vocalisation. Lesions in Broca's area causes loss of grammatical articulation but comprehension is maintained. Wernicke's and Broca's areas are connected by the arcuate fasciculus nerve fibre bundle. The linguistic dominance of the left cortical hemisphere is apparent anatomically as the posterior part of the planum temporale which forms part of Wernicke's area is larger on the left than on the right with a distinctive cellular layered architecture. The length and orientation of the sylvian fissure on the two hemispheres differ in humans, apes and hominids but not in monkeys. Such left hemisphere cerebral dominance has been found in the skulls of Neanderthal man, great apes and other hominids. The parieto-occipital area of the right hemisphere analyses non-mathematical and non-linguistic spatial relationships and the temporal region processes non-spatial stimuli such as music. Each hemisphere learns independently with learned information being transferred through the corpus callosum joining the two cerebral hemispheres. Thus information is passed, mediated and integrated across the two hemispheres through the corpus callosum. This transfer of ~4x10^{9} impulses/second does not occur if the corpus callosum is severed. If the corpus callosum is severed (as insevere epileptic patients), the two hemispherss of the brain function normally but independently as two separate brains [Sperry 1964]. Under normal circumstances, no change in behaviouyr is observed. In such split brain patients, visual and tactile information is presented to a particular hemisphere band dealt with normally within the specialisations of that hemisphere. For instance, information presented to the left hemisphere can elicit verbal and written responses, while such responses are absent when presented to the right hemisphere. Under normal circumstances, feedback from the environment prevents abnormal behaviour.

Frontal brain structure are involved in temporal integration. Temporal perception involves subjective phenomena including simultaneity, succession, order, continuity, etc. Neural oscillations with reaction times ~30 ms provide the basis for temporal perception as there are no receptors for "time" [Poppel 1997]. The prefrontal cortex has a supervisory and anticipatory role (expectancy) in the planning of our future behaviour. It organises anticipatory behaviour in a top-down way by activating cortico-cortical and thalamo-cortical loops to sensory and motor areas to command these areas [Brunia 1999].





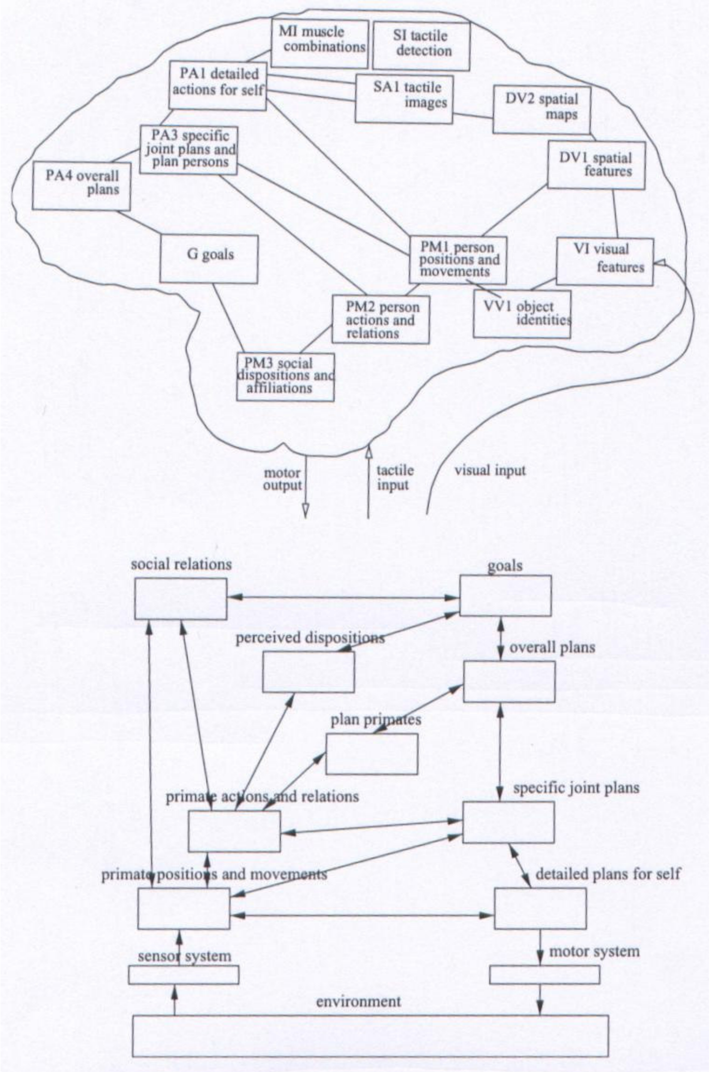


Fig D-3 (a) Closed loop of motor circuitry; (b) Major connections between cerebellum, basal ganglia, thalamus and motor cortical areas; (c) Neocortical model as perception-action hierarchy [from Brunia 1999]

All thalamocortical fibres are reciprocal. The thalamic reticular formation sends no afferents to the cortex and has a local inhibitory influence on thalamic relay, suggesting a role in selective attention, ie. the reticular formation selects attention between sensory modalities and inhibits irrelevant motor behaviour. The frontal cortex has small regions that are connected to immediately neighbouring regions and to widely distributed regions throughout much of the frontal lobe. However, there are also subregions of the frontal cortex that have differentiated, modular architectures, yet appear to have very general functions. Working memory is generally attributed to the frontal cortex. The frontal lobes exhibit a range of activation patterns for different cognitive tasks [Duncan & Owen 2000]. For many cognitive demands, recruitment of mid-dorsolateral, mid-ventrolateral and dorsal anterior cingulated cortex in both hemispheres is consistently observed. Most of the remainder of the frontal cortex (medial and orbital surfaces) are generally insensitive to such cognitive loads. It appears that there is regional specialisation of function within the prefrontal cortex and that a specific frontal lobe network across these three frontal cortical regions is consistently recruited for solving diverse cognitive problems such as response selection, working memory rehearsal and stimulus recognition. Theory of mind also appears to reside in several frontal cortical structures including right orbito-frontal cortex and the left medial frontal cortex (specifically Brodmann's areas 8 and 9 and the anterior cingulated) [Stone et al 1998]. Theory of mind refers to the ability to make inferences about other agents' mental states and is fundamental to human social interaction. It is subject to selective impairment as evidenced by autism and Asperger's syndrome suggesting that it is a modular capacity. This is further supported by its universality, stereotypical developmental sequence and automatic function.

BRAINSTEM

The brainstem is the central core of the brain and comprises all brain matter except the cerebral cortex and the cerebellum. Its main components are the spinal cord, medulla, pons, and the old cortex. The old cortex comprises the diencephalon (thalamus, hypothalamus and basal ganglia) and midbrain (mesencephalon). The medulla is continuous with the spinal cord. Some fibres emerge through the medulla while others emerge into a more complex, diffuse arrangement of fibres and cells to become the reticular formation which extends through the medulla, pons and upper brain stem. All the cranial nerves emerge from the brainstem into their respective nuclei. The vestibular nucleus lies in the medulla which receives afferent fibres from the vestibular division of the acoustic nerve via the pons. The pons comprises two parts – the tegmentum and basilar containing pyramidal tracts which disperse with corticopontile tracts from the frontal, temporal, parietal and occipital cortex. The pons includes attachment structures for the cerebellum and the pontile nuclei which connect to the cerebellar cortex. The corticopontile fibres flank pyramidal tract from the basilar pons that forms the midbrain. The diencephelon is bounded by the corpus callosum from above and the corpus striatum which bound it laterally. It is divided into two hemispheres. The hypothalamus is located in the centre of the diencephelon. The second part is the thalamus and the third part is the subthalamus. The thalmus and hypothalamus produce sleep. The hypothalamus at the base of the forebrain regulates the activation of autonomous nervous system and also involves emergency reactions to stimuli. Short term regulation of autonomous systems (eg. the circulo-respiratory system) is controlled by the medulla oblongata. Almost all sensory inputs (except olfactory) to the cortex pass through the dorsal thalamus (the major part of the thalamus) and for each projection to the cortex from the cerebellum has a corresponding reverse projection back to the thalamus. The major component of the ventral thalamus comprises the reticular formation which surrounds the dorsal thalamus. Hence, all projections to and from the thalamus pass through the reticular formation. The output neurons of the thalamus are excitatory while the output neurons of the reticular complex are inhibitory. The searchlight hypothesis suggests that the reticular formation provides the means for a thalamocortical positive feedback loop. This provides the means to focus attention by selecting the most active part of the thalamocortical map for interpolation [Crick 1984]. The hypothalamus comprises of grey matter with sixteen ill-defined nuclei. The hypothalamus sends fibres to the reticular formation of the midbrain. There are two sensory inputs from the hypothalamus to the sensory nuclei of the thalamus. The reticular formation sends fibres to the hypothalamus and thalamus. The main efferent connection to the hypothalamus is the fornix which originates from the hippocampus. The reticular formation of the brain stem is constructed from parallel stacks of discs of neural tissue. The reticular formation sends impulses to almost all areas of the cerebral cortex to control the degree of alertness and the deployment of attention for selective stimuli-response. Thus the reticular system is responsible for general arousal and activity and for the control of attention. It receives input from a wide of sources - the motivational regions, sensory system and the cerebral cortex. The hypothalamus also controls the autonomic system associated with emotional responses.

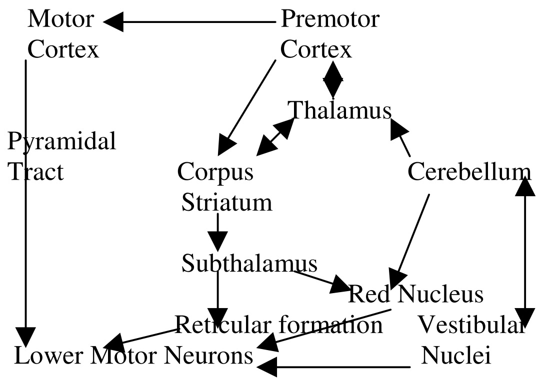
The midbrain and hindbrain are non-specific in terms of sensory modality with the multi-modal reticular formation receiving homegeneous inputs.

THALAMUS

The thalamus lies in the dorsal portion of the diencephalon and is continuous with the hypothalamus and subthalamus. It serves as a relay station for efferent impulses of all types prior to transmission to the cerebral cortex. It integrates and fuses stimuli and focusses attention. All connections of the thalamic nuclei to the cerebral cortex are augmented with reciprocal feedback fibres back to the thalamic regions from whence they receive their inputs – the visual cortex projects back to the thalamic lateral geniculate; the auditory cortex projects back to the thalamic medial geniculate; and the somatic sensory cortex projects back to the thalamic ventral nucleus. This suggests that the cortex influences earlier stages of sensory processing. All thalamic nuclei communicate with each other through short fibres. The lateral geniculate body of the thalamus receives the optic tract and connects them to the primary visual cortex. The medial geniculate body of the thalamus receives input from the temporal gyrus (hearing). The posterior ventral nucleus is the main sensory nucleus of the thalamus receiving inputs from touch, proprioception, pain and temperature which are relayed to the somatasensory cortex. The anterior nucleus of the thalamus acts as a relay station receiving inputs from the hypothalamus and sends them onto the limbic system. The medial nucleus of the thalamus is reciprocally connected to the frontal cortex and the hypothalamus. The anterior ventral nucleus of the thalamus has afferent and efferent connections to the pre-motor cortex. The ventral intermediate of the thalamus receives fibres from the cerebellum, integrates motors activity, and projects them to the motor and pre-motor cortex. The lateral nucleus of the thalamus connects reciprocally to the parietal cortex and receives fibres from other thalamic nuclei, but its function is unknown. The pulvinar connects reciprocally to the parietal, temporal and occipital cortex at the junction, but the function is this circuit is unknown. The habenular nuclei at the base of the pineal body acts as a realy station for olfactory inputs which are passed to the midbrain. The thalamic reticular system comprises a number of dispersed nuclei in the thalamus resembling the reticular activation system of the midbrain and hypothalamus. Both are interconnected subcortically. It extends fibres widely across the cerebral cortex which modify cortical activity.

SUBTHALAMUS

The subthalamus and corpus striatum control instinctive and stereotypical motor activity associated with habit and automatic activities. The pyramidal system relies on the vestibular system, the cerebellar system and the corpus striatum. The extrapyyramidal system comprises The caudate nucleus and global pallidus are shared by the corpus striatum and the basal ganglia. The thalamus sends fibres to the caudate nucleus. The basal ganglia also includes the amygdala, substantia nigra and subthalamic nucleus. The corpus striatum also includes the putamen. The subthalamus is closely related to the corpus striatum in function and contains the subthalamic nucleus and outerlying substantia nigra and red nucleus. The putamen and globus pallidus receive fibres from substantia nigra. All efferent fibres from the corpus striatum originate from the globus pallidus which pass to the subthalamus, some terminating on the subthalamic nucleus, while others pass through to terminate on the thalamic nuclei or the red nucleus. The caudate nucleus sends most of its afferent connections to the putamen which sends fibres to the globus pallidus. The caudate nucleus and putamen inhibit activity of the globus pallidus which provides motor facilitation.



The major cranial nerves are complex in their pathways but they are listed as:

(i) unassigned
(ii) optic nerve conveys visual data to the brain
(iii) pupillary nerve controls eye focus of the lens and keeps the eye inwardly convergent
(iv) trochlear nerve is a motor nerve of the eye that turns it obliquely downwards and outwards
(v) trigeminal nerve controls the mouth and jaw
(vi) abducent nerve is a motor nerve of the eye that prevents the eye from converging inwards
(vii) facial nerve which controls the facial muscles and closes the eyelids
(viii) acoustic/vestibular nerve which conveys hearing and balance to the brain
(ix) glossopharyngeal nerve controls the front of the tongue
(x) vagus nerve is a complex nerve that controls pharyngeal/laryngeal muscles, the heart, lungs and abdominal viscera
(xi) spinal accessory nerves supply the mastoid and trapezius muscles
(xii) hypoglossal nerve is the motor nerve of the tongue

HYPOTHALAMUS

The hypothalamus is located in the diencephalon below the thalamus – it regulates the autonomic nervous system and pituitary gland. The hypothalamus maintains homeostasis by regulating body temperature, blood flow, glucose levels and synchronises the circadian rhythm with the daily cycles of light and dark. The magnetocellular neurons of the hypothalamus project into the posterior lobe of the pituitary gland. Hormones are released from the pituitary into the bloodstream. Vasopressin regulates blood volume and salt concentration by altering water retention through feedback from the kidneys via the release of rennin and activation of angiotensin thereby controlling thirst. The hypothalamus also regulates the anterior pituitary gland through the release of large peptide hormones affecting G-coupled receptors of the reproductive organs, the thyroid, adrenal cortex and other organs, eg. andrenocorticotropin (ACTH) secretes cortisol to regulate the immune system. The autonomic nervous system regulates bodily functions such as heart rate, blood pressure, gastrointestinal motility and glandular activity. The sympathetic component uses norepinephrine or epinephrine while the parasympathetic nervous system uses acetylocholine.

BASAL GANGLIA

In sequential movements, different actions are generated in a certain order. The serial order of actions – the motor plan – may be represented by the temporal order of neural discharges. The basal ganglia and cerebellum are associated with the control of movement. The motor cortex sends information to both structures and both feed back signals to the motor cortex. The output from the cerebellum is excitatory while that from the basal ganglia is inhibitory. All inhibitory interneurons use γ-aminobutyric acid (GABA) as their primary transmitter. Both contribute to smooth coordinated motions. The basal ganglia are the largest subcortical structures in the human forebrain. The basal ganglia lies deep within the cerebral cortex and includes the caudate, putamen, nucleus accumbens (collectively the striatum), global pallidus (with striatum form the corpus striatum), substantia nigra, and subthalamic nucleus [Graybiel 2000].

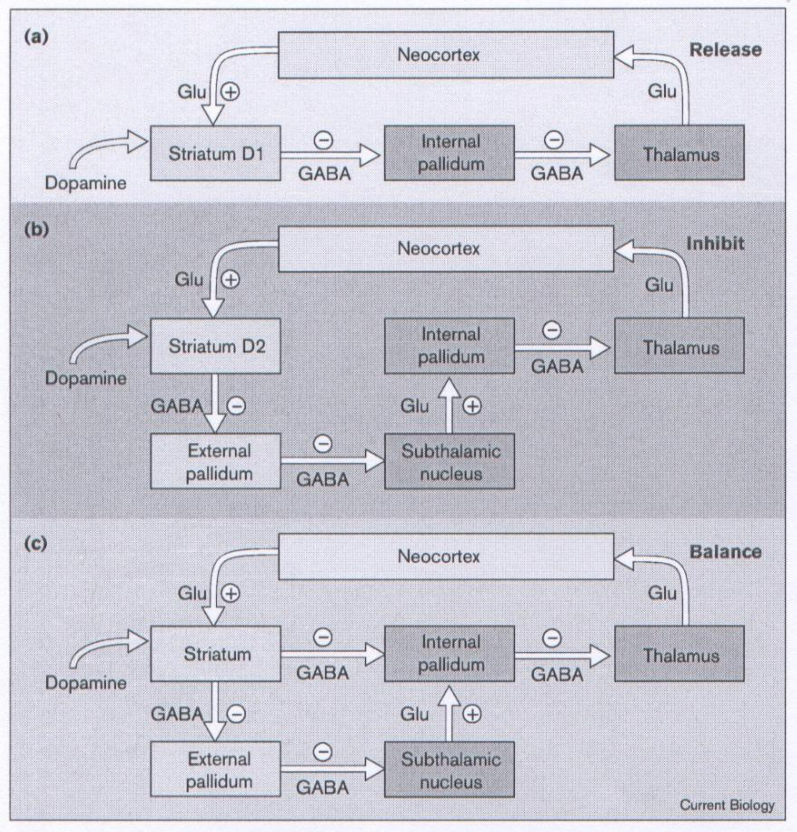


Fig D-4 Brake-accelerator model for basal ganglia motor function (a) direct pathways of two successive GABAergic connections from striatum to internal pallidum and from internal pallidum to thalamus (excitation of motion); (b) indirect pathway which requires an extra step after external pallidum (inhibition of motion); (c) balance between these antagonistic systems [from Graybiel 2000]

The neostriatum is the largest component of the basal ganglia and are primarily GABAergic. The caudate and putamen act as gateways to the basal ganglia and receive most of the input from the cerebral cortex. The pallidum receives most of the output from the striatum. The medial caudate and nucleus accumbens receive input from the frontal cortex and limbic system and are associated with higher level cognition rather than movement. The caudate and putamen are reciprocally connected with the substantia nigra and send most of their output to the globus pallidus. The substantia nigra controls head and eye movement and produces dopamine for normal movement. The globus pallidus receives input from the caudate and putamen and sends inhibitory output to the thalamus which in turn projects to the frontal cortex. The basal ganglia thus acts as a brake in the planning of movement. Direct excitation of the thalamus via two successive GABAergic connections from the striatum to the pallidum is opposed by indirect inhibition of the thalamus. Inputs to the striatum from dopamine containing neurons of the midbrain deliver reward-predictive signals. A neural model of closed loop circuits connecting the striatum, internal globus pallidum, and substaantia nigra pars compacta, thalamus and cortex has been constructed [Fukai 1999].

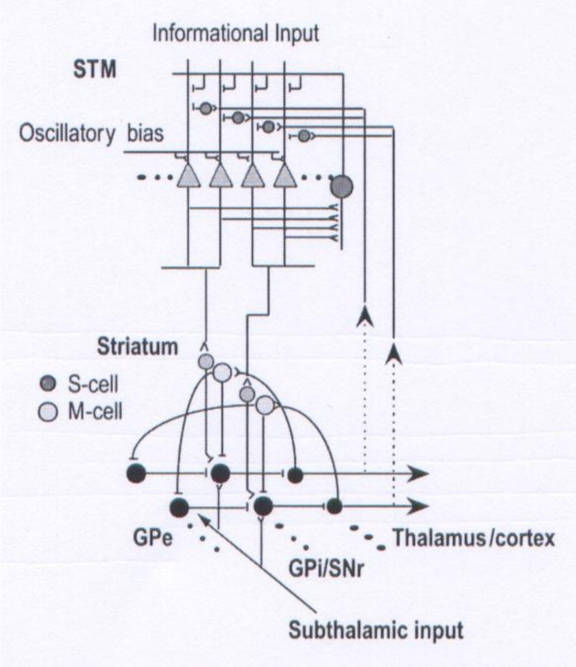


Fig D-5 Neural circuitry of short term memory and cortico-basal ganglia-thalamic loops [from Fukai 1999]

The striato-globus pallidus-substantia nigra and globus pallidus-substantia nigra-thalamus pathways are inhibitory while the thalamo-cortico-striatal projections are excitatory. Redgrave et al (1999) have suggested that the basal ganglia solves the selection problem when two or more competing systems are attempting to simultaneously access a limited resource by introducing a central switching mechanism. The basal ganglia resolves conflicts over access to limited motor resources and selects some motor actions at the expense of others through a winner-takes-all strategy. This may be implemented through a distributed network of recurrent reciprocal inhibition links requiring n(n-1) connections but a central selection mechanism requires only 2n connections. The basal ganglia might function as such a centralised selection mechanism.

VESTIBULAR & CEREBELLAR SYSTEM

The vestibular system is the most anciemt sensory system in providing balance equilibrium and orientation. Mammalian evolution has added a cochlea for hearing to this system, so there are two divisions to the 8th cranial nerve – the vestibular and acoustic pathways. The cochlea receives sound vibrations through the perilymph of its spiral chambers. The organ of Corti perform audiofrequency analysis. Fibres synapse with the hair cells of the organ of Corti which pass as the cochlear nerve into the medulla to synapse on the cochlear nuclei at the junction with the pons. Some fibres from the cochlear nuclei pass to the nucleus of the abducent nerve, and onto the nucleus of the oculomotor nerve to provide conjugate horizontal eye movement in response to sound. Other fibres from the cochlear nuclei pass to the medial geniculate body of the thalamus which relay the signals to the primary auditory cortex (area 41).

The vestibular system bears similarities with the acoustic system, particularly the transduction mechanism. The vestibular sensors comprise of hair cells within the utricle and saccule and hair cells in the ampullae of the three orthogonal semicircular canals. The horizontal canal lies at an angle of 30^o away from the horizontal. Afferent fibres from the 8th nerve provide the basis for coordination of eye movements, and head, neck and body posture. Axons of the vestibular ganglion follow the cochlear nerve to the medulla terminating on the four vestibular nuclei. Some fibres pass directly to the cerebellum which connect to the fastigiobulbar tract which exit the cerebellum and returns to all four vestibular nuclei in the brainstem. Two vestibulospinal tracts emerge from the vestibular nuclei which pass down the spinal cord to the mucles of the limbs for posture maintenance. Fibres from two of the vestibular nuclei form the vestibulomesencephalic tract to the motor nuclei of the oculomotor nerve which control the ocular muscles of the eyes. This enables the eyes to remain fixed on objects while the head and body move.

There are two main non-pyramidal systems controlling movement: the cerebellum and the extrapyramidal system. The cerebellum is the major component of the rhombencephalon. It is attached to the pons and medulla by the cerebellar punducle. The cerebellum comprises $\sim 10^{11}$ granule cells. The cerebellum is primarily responsible for muscular coordination and regulation of motor skills – indeed, unlike the case of the cerebral cortex, each cerebellar hemisphere controls its own side of the body. The cerebellum acts as a spatio-temporal pattern discriminator while the cerebrocerebellar loop is used as a reference model for open loop control. The cerebellar cortex is the corrugated outer layer of grey matter enclosing a core of white matter. The cerebellar cortex consists of neurons arranged in highly ordered repeated patterns. It comprises several types of neurons:

(i) long axoned input excitatory climbing and mossy fibres conduct impulses to inhibitory outputs;
(ii) Purkinje cells of the cerebellar cortex with extensive dendritic inputs of 10^5 synapses forming a continuous parallel array layer with dendrites extending towards the cortex and axons extending towards the underlying granule cells;
(iii) long axoned excitatory granule cells;
(iv) short axoned inhibitory Golgi basket and stellate cells act as intermediate neurons between the input and output neurons.

The Purkinje cells prevent the transmission of impulses from the input fibres that would otherwise reach motor neurons and generate movement. Some secondary sensory neurons in the spinal cord and hindbrain channel directly into the cerebellum.

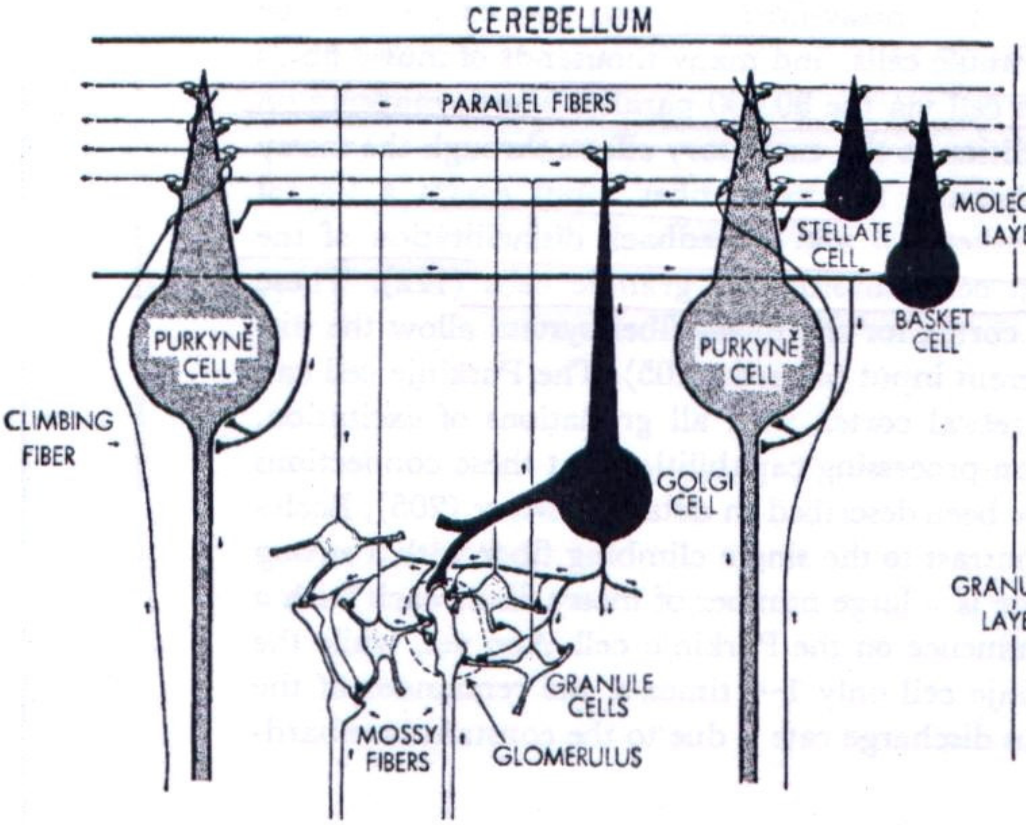


Fig D-6 Neuronal connections within cerebellar cortex [from Allen & Tsukahara 1974]

The cerebellum is divided into two cerebellar hemispheres fused at the mid-line. The central part of the cerebellum (vermis) is concerned with equilibrium and maintains balance when the centre of gravity of the body changes. The flocculonodular lobe comprises paired appendages (flocculi) at the posterior and represents the cerebellar portion of the vestibular system – it is evolutionarily the oldest part of the cerebellum. The anterior lobe receives most of the proprioceptive impulses from the spinocerebellar pathway. Both lobes are prominent in primitive vertebrates. The middle lobe is the main part of the cerebellum and receives input from the cerebral cortex – it is expanded as a neocerebellum in mammals. The fastigiobulbar tract travels from the cerebellum to the vestibular nuclei to close the vestibular circuit. Afferent fibres also come into the cerebellum from the vestibular nerve. The cortex of the cerebellum controls voluntary motor activity by commands issued from the motor cortex through the corticopontocerebellar pathway, and through feedback through the spinocerebellar tract from the muscles. It does not initiate motor actions but receives inputs from the motor cortex and proprioceptive inputs [Llinas 1979]. Each proprioceptive nerve in the skeletal muscles map onto climbing fibres organised into strips over the cerebellar cortex. Corrections to inaccuracies of muscular activity are dispatched as nerve impulses from the detate nucleus. Ataxias result from cerebellar damage which result in postural or gait disequilibrium, uncoordinated movements and overshoot movements.

The cerebellum is involved in the maintenance of posture, timing coordination of voluntary movement and compares movement intention from the motor cortex with proprioceptive feedback from the limbs and corrects the movement. The cerebellum operates ipsilaterally rather than contralaterally as in the cerebrum. There are three inputs to the cerebellum: mossy fibres from spinocerebellar pathways, climbing fibres from inferior olive, and further mossy fibres from the pons carrying information from the cerebral cortex (where they cross from contralateral to ipsilaterally). The cerebellum has a highly convoluted cortex (of Purkinje cells) around inner white matter and deep nuclei. Each fold of the cerebellum has a characteristic structure of Purkinje cells around a dense layer of granule cells all surrounding a central core of white matter. Mossy fibres provide input to the cerebellar cortex and enter the granule cell layer and synapse with granule cell dendrites. Granule cells send their axons to the surface of the cerebellar cortex and form parallel fibres. The parallel fibres synapse on the dendritic arrays of Purkinje cells. Purkinje dendrites fan out and the parallel fibres run perpendicular to the Purkinje cells and make contact at the intersections. Each parallel fibre touches each Purkinje cell, there are thousands of such connections. Climbing fibres also input into the Purkinje cells, each climbing fibre being associated with one Purkinje cell. The Purkinje cell compares the inputs and outputs through the white matter to the deep nuclei – the three deep nuclei are the fastigial nucleus concerned with balance and outputs to the vestibular and reticular system, interposal nucleus concerned with voluntary movement and outputs to the thalamus, and dentate nucleus concerned with voluntary movement and outputs to the red nucleus. Although the inhibitory Purkinje cells are the main output, the cerebellar cortex excitatory output comes from the deep nuclei to the thalamus and postural and vestibular centres. Synaptic plasticity in Purkinje cells is essential for adaptive control of vestibular-ocular reflex (VOR). The vestibular-ocular reflex is an open loop reflex whereby head velocity detected by the vestibular system causes eye movements of equal and opposite velocity. This is critical in head-eye coordination and stabilisation of vision during head movements. The gain of VOR is modified by detection of slippage velocity of the visual image on the retina.

The cerebellar cortex is constructed from four types of neuron which form a lattice-like structure – granule cells, Purkinje cells, Golgi cells and stellate/basket cells [Voogd & Glickstein 1998]. It receives inputs from mossy fibres and climbing fibres. Granule cells are small glutamergic neurons and are very common. Granule cell dendrite receive inputs from mossy fibres and output on Purkinje cells in the cerebellar cortical surface. Purkinje cells are large GABAergic neurons which are the output cells of the cerebellar cortex. Golgi cells provide feedback inhibition to granule cells while stellate/basket cells provide feedforward inhibition to Purkinje cells. The cerebellum exhibits an evolutionary history of increased complexity from simple dome-like structures in amphibians and reptiles to more complex structures in fish, birds and mammals. In fish, the cerebellum has a central mass with two lateral nucei of the lateral line. In birds and mammals, the cerebellum is foliated, this foliation being more complex in mammals. The most caudal lobules – the nodulus and flocculus – have Purkinje cells projecting to the vestibular nuclei. The cerebellum appears to have a role in sensorimotor learning and memory such as classical conditioning of the eyeblink through synaptic plasticity in Purkinje cells [Kim & Thompson 1997].

There are functional connections between the cerebral cortex and the cerebellar cortex [Allen & Tsikuhara 1974]. The cerebral cortex and cerebellum have one major difference – pyramidal cells in the cerebrum are excitatory while Purkinje cells in the cerebellum are inhibitory. The main motor output pathway from the motor cortex is the pyramidal tract which innervate a number of brainstem nuclei, some of which project into the cerebellum, namely, the pons (source of mossy fibres), inferior olive (source of climbing fibres) and lateral reticular nuclei (source of mossy fibres). Within the cerebellar cortex, mossy fibres and climbing fibres inputs affect Purkinje output cells in different ways. Climbing fibres innervate ~10 Purkinje cells generating intense depolarisation of Purkinje cells. Each mossy fibre innervates ~460 granule cells and many thousands of mossy fibres influence each Purkinje cell via the 80,000 parallel fibres. This exerts a lateral feedforward inhibition via basket cells and feedback inhibition of the Purkinje cell by Golgi cell inhibition of granule cells. Purkinje cell activation via climbing fibres has a latency of 12-20 ms while mossy fibre inputs have a wide range of latencies. Purkinje cells summate the cortical inputs representing the motor command and spinal input representing movement from previous motor command (proprioceptive feedback). There exists somatropy with the sensorimotor cortex such that Purkinje cells inn lobules III and IV receive mossy and climbing fibre inputs from the hindlimb area of the sensorimotor cortex while Purkinje cells in lobules V and VI receive inputs from forelimb area of the sensorimotor cortex. The Purkinje output cells inhibit cerebellar nuclei, the most important of which is the ventrolateral thalamic nucleus which inputs to the motor cortex.

Common neural processes are used for both imagined and actual movements. Mental rotation studies indicate that a rotated object is mentally represented at equally spaced durations forming a near continuous rotation in 3D space from its initial to its final orientation. The time to complete the imagined rotation is a linear function of the rotation angle. The cerebellum appears to have a critical role in such imaginings despite no motor action taking place. Indeed, the cerebellum has been implicated in all types of non-motor activity – semantic word generation, temporal order perception, planning, spatial reasoning, etc. However, removal of the cerebellum produces mild deficits. The cerebellum's three to fourfold increase in size during the last million years indicates that it has a crucial role in mental skills through its outputs to the frontal cerebral cortex via the thalamus, perhaps as part of the requirement for accurate throwing.

LIMBIC SYSTEM

The James-Lange theory of emotion suggests that environmental stimuli produce bodily responses and it is these bodily effects that give rise the "feelings" of emotion. This theory has been invalidated. Motivation is a form of arousal that is required to execute complex behaviour but its neural basis is not currently known, except for appetitive motivational states like hunger and thirst which are controlled by the hypothalamus [Grossman 1979]. Non-homeostatic motivation and emotion are considered as reinforcement mechanisms for learning and interfacing between senses-brain-action. Reward and punishment are computed and used for selecting appropriate actions. Emotions allow learning of environmentally-tuned behaviours beyond simple taxes. Frustration and anger is generated by the absence of expected reward while relief is produced by the absence of expected punishment. Emotions are generally elicited by external events while motivations may also be internally generated (eg. hunger, thirst). Emotions cause autonomic responses in preparation for action and as a form of action selection provide a more direct interface between sensory inputs and effector actions. Fear is a stimulus-reinforcement association for avoiding punishing stimuli.

The limbic system in the medial temporal lobe comprises the olfactory cortex, amygdala and the hippocampus. The amygdala is the nucleus primarily responsible for mood and emotional responses including fear response. There are two basic systems – one for appetitive approach behaviours with positive affect and the other for aversive withdrawal behaviours with negative affect [Davidson & Irwin 1999]. The prefrontal cortex is important for both positive (left anterior prefrontal cortex) and negative affect (right anterior prefrontal cortex) due to anticipation of future affective consequences. The amygdala is differentiated from olfactory cortex, claustrum or striatum [Swanson & Petrovitch 1998]. Input to the amygdala is highly processed information from the visual, auditory and somatosensory cortices. It is connected to the frontal cortex, mediodorsal thalamus and medial striatum.

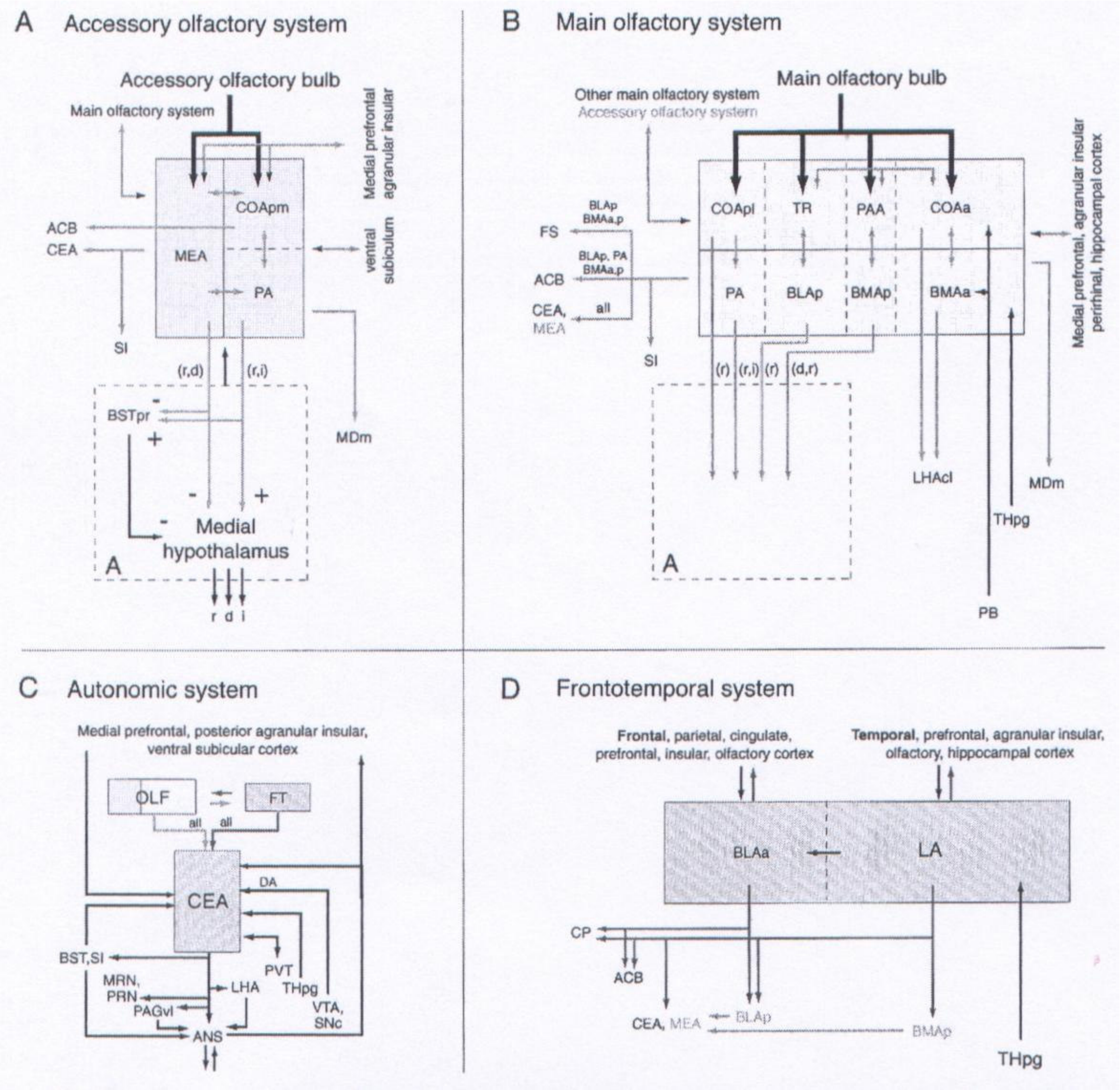


Fig D-7 Major neural inpuits and outputs of accessory and main olfactory systems to autonomic and striatum [from Swanson & Petrovitch 1998]

The amygdala plays a role in determining whether a stimulus is dangerous or not and projects back to cortical sensory processing systems but not the thalamus [LeDoux 1995]. It outputs to the hypothalamus and brainstem autonomic nervous system (such as the medulla oblongata) to provoke a sympathetic response. The amygdala shows theta activity during emotional arousal and exhibits long term potentiation during emotional learning such as during aversive Pavlovian CS-US fear conditioning.

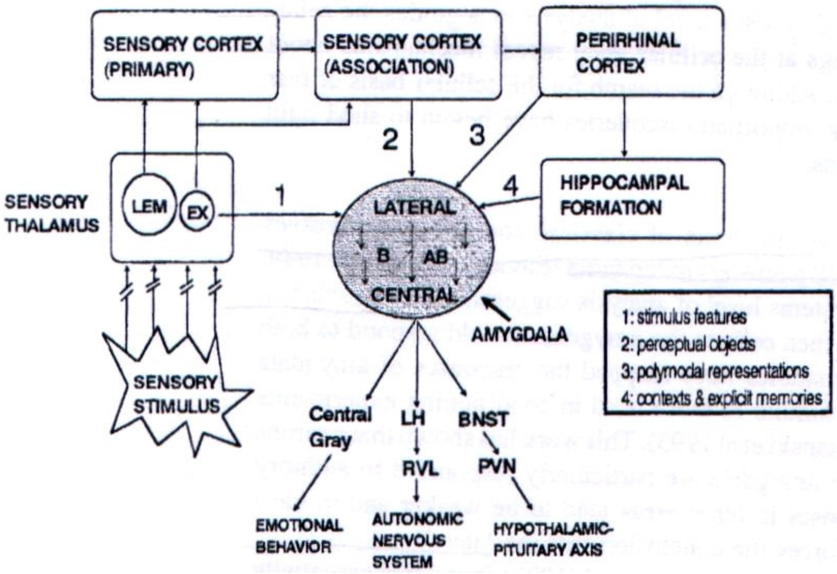
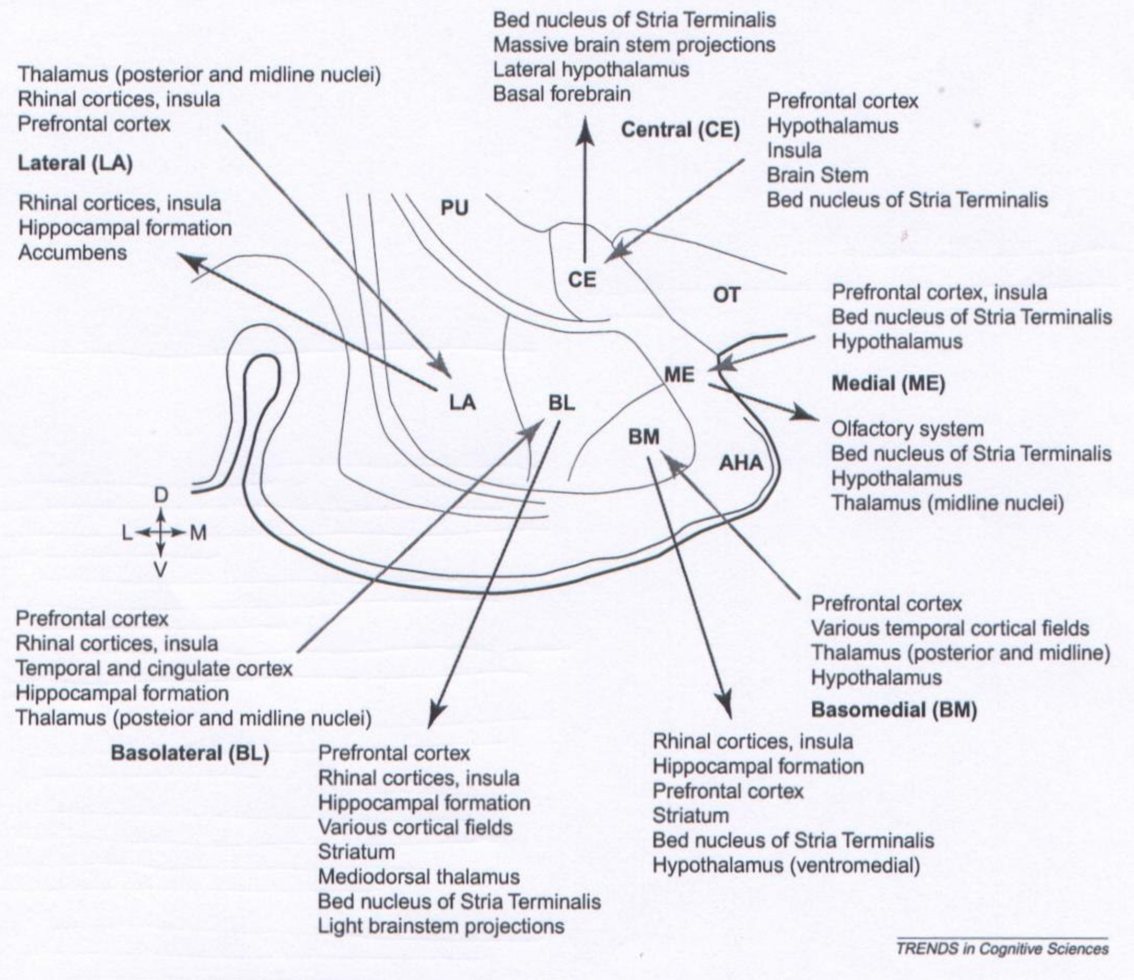


Fig D-8 Neural circuits of fear conditioning [from LeDoux 1995]

Long lasting enhancement of synaptic strength defines long term potentiation. The amygdala is responsible for both positive and negative affect, but negative affect is dominant. Serial processing by the basolateral and central nuclei of the amygdala is the main site of fear conditioning – the amygdala assigns emotional value to events during associative learning [Holland & Gallagher 1999]. Emotional stimuli – both positive and negative - enhances memory encoding and consolidation through the action of the amygdala through increased attention and stress hormone (adrenaline and corticosterone) release respectively [Cahill & McGaugh 1998, Hamann 2001]. Evidently, there are sound survival and reproductive reasons for this. Stress hormones interact with the amygdala which affect memory consolidation within the hippocampus. In particular, the basolateral region of the amygdala which projects to the hippocampus, caudate nucleus and cortex is implicated in this process through stress hormone regulation of its noradrenaline receptor activity [McGaugh 2002]. The central nucleus of the amygdala projects into the hypothalamus, midbrain and medulla that control a number of defensive responses including startle and freezing [Gallagher & Holland 1994]. The amygdala also shows synchronised neural oscillations during sleep which may enhance interactions between temporal lobe hippocampal system and neocortical storage sites for the laying down of long term declarative memory [Pare et al 2002].



TRENDS in Cognitive Sciences

Fig D-9 Main connections of amygdala: AHA (amygdalohippocampal area), OT (optical tract) [from Pare et al 2002]

Slow wave sleep (<1 Hz and 1-4 Hz) enhances cortical reorganisation of ocular dominance columns during visual cortical development and for the consolidation of visual procedural memory such as visual discrimination skills. Slow wave sleep also enables transfer of episodic information stored in hippocampal CA3 to the association cortex through long-term synaptic changes. Such a delayed mechanism allows the significance of the event to be evaluated before long-term storage.

VISION PROCESSING

Animals devote a significant fraction of their nervous system to vision and other sensory processes – the sensory cortex is estimated at 25% of the cerebral cortex in humans. Biological visual processing is based on feature detection involving three different regions of the brain: the retina, the lateral geniculate nuceus and the visual cortex. The first work on visual processing on the frog [Lettvin et al 1959] determined that visual processes were independent of general illumination and involved image processing of:

(i) sharp edges and contrasts;
(ii) edge convex curvature of objects;

(iii) movement of edges;
(iv) dimming caused by object extent.

Each fibre group from the retina mapped into parallel sheets in the frog's tectum, one sheet and group for each of four operations. The visual processing hardware connections were non-random and was geared towards "bug perception" for catching food items of a given size and motion.

An image is formed by the lens on the retina that is inverted and reversed on the retina. The first layer is that of the photoreceptive retina which detects light signals and transforms them into electrical signals. Photons are absorbed by the photopigment rhodopsin in the membranes of photoreceptor rod or cone cells of the retina to produce an electrical output. The retina comprises of 1.2 x 10^8 cone and rod cells. Cells near the fovea have small receptive fields for precise determination while cells away from the fovea have larger receptive fields (particularly for night vision) [Hubel & Weisel 1979]. The second layer comprises two concentric layers of 1.2 x 10^6 retinal ganglion cells – on-centre and off-centre arrays with a centre-surround arrangement. The retinal cells sends impulses to the bipolar retinal cells and retinal ganglion cells. The retina performs preprocessing of the visual information. The retinal ganglion cells enhance relative illumination differences for greater contrast. Each cell is divided into circular symmetric exhitatory centre and an inhibitory surround generating concentric receptive fields with illumination contrast comparison. Response fields overlap many neighbouring units whose peak sensitivities vary from neuron to neuron systematically. Local feature extraction is enabled by centre-surround oriented intensity discontinuities. The gains of these cells decrease exponentially with distance from the centre to act as filters to locate boundaries of objects in the visual field by comparing illumination levels between neighbouring regions of the visual field. The ~10^6 axons of the retinal ganglion cells converge into the fibre optic bundle and output along the optic nerve. Signals representing each half of the visual field from each eye cross over to the opposite hemisphere of the brain at the optic chiasm. From there, the majority of the retinal ganglion cells terminate on the neurons of the left and right lateral geniculate nucleus of the thalamus either side of the brain stem. Some project into the superior collicus of the midbrain before projecting into the posterior lateral nucleus of the thalamus, and then onto the visual cortex. Some of the fibres bypass the visual cortex projecting into the oculomotor nucleus and then onto the iris – this is the basis of the pupillary light reflex. There are additional reflexes of the eye with a similar architecture – the optokinetic reflex which comprises afferent pathways from the retina to the visual cortex onto the superior collicus from which fibres project into the motor nuclei of cranial nerves 3, 4 and 5. The thalamus is involved in the focus of attention and acts as a relay station for all sensory information except olfaction. It transforms all sensory signals into a code suitable for the cerebral cortex. The thalamus sends the signal along the lateral geniculate axons to the striate or visual cortex (Brockmann's area 17) on the occipital lobe. Hence, there are two visual channels ascending to the cerebral cortex. The visual cortex comprises several layers II, III, IV, V and VI which are subdivided into a large number of vertically arranged columns of neurons. The retinal connections via the lateral geniculate nucleus connect into the visual cortex (at area IV). The retinal connections to the visual cortex are topographically arranged, bearing direct correspondence to the receptive fields such that neighbouring cells have neighbouring receptive fields. The cortical neurons differentially respond to directed line and edge segments at specific orientations. Simple cells in the upper part of layer IV respond to specific positions and orientations of lines while circularly symmetric cells reside in the lower part of layer IV. Layers II, III, V and VI comprise of complex cells which can also detect orientation-specific lines but are less position-specific. Layer III responds only to line orientation. Layer V responds to motion and direction. Layers I and II coordinate these parallel systems. This is the first step towards extracting features. The visual cortex outputs to areas deep in the brain and to nearby parts of the cortex. All thalamocortical projections are reciprocated – Layer VI of the visual cortex projects feedback fibres back from the visual cortex to the lateral geniculate nucleus, Layer V to the superior collicus in the midbrain, Layers II and III to other parts of the cortex, for combination of the receptive fields into more complex fields for higher levels of image recepresentation. Similarly, the auditory cortex projects fibres back to the medial geniculate body, the somatosensory cortex projects fibres back to the ventral nucleus. Hence, the state of the cortex influences processing in the thalamus through feedback mechanisms. From the sensory cortex, fibres project to adjoining sequences of the association cortex which represent the largest fraction of the cortex for more advanced processing including the fusion of auditory and visual information. The final destination of such processing lies in the hippocampus and amygdala. The amygdala is a nucleus near the tip of the hippocampus which receives input from the olfactory tract and outputs to the hypothalamus. There are two cortical regions controlling gaze in each cortical hemispheres – the premotor cortex controls scanning and roving eye movements; the visual cortex controls object tracking, pursuit and saccade reflexes. Observer motion is compensated for through vestibular and proprioceptive feedback from the cerebellum.

The visual field is broken down into receptive fields and processed through a series of filters. The iris of the eye is controlled by the papillary sphincter muscle which constricts the pupil under the parasympathetic system and the papillary dilator muscle which open the pupil under the sympathetic system. Around 130 million photoreceptors in the retina detect illuminance in the visual field. The retina is a seven-layered structure with light entering the ganglion cell layer penetrating through all layers to reach the photoreceptors at the base of the layer. Photoreceptors include both rods and cones, rods being at their highest density at the fovea, rods being concentrated at peripheral vision. Rods are far more numerous than cones and provide black and white vision, sensitive to low light levels while cones provide colour vision. Cones pass to the small ganglion cells and are sensitive to colour while rods pass to large ganglion cells and are sensitive to motion – this separation is maintained up to V2 region of the visual cortex. The visual field of each eye is divided into right and left hemifields which partially cross at the optic chiasm. This information is compression in around one million ganglion cells which form the optic nerve (which creates the blindspot) and pass through the optic chiasm to the lateral geniculate bodies of the thalamus where all optic tract neurons synapse. The retinal ganglion cell responds to a roughly circular spot of light presented to a specific part of the visual field. Some ganglion cells have on-centre receptive fields, others off-centre receptive fields (centre-surround) generated by the bipolar and horizontal cells of the retinal interneurons through neighbouring inhibition by horizontal cells [Hubel & Wiesel 1962]. The receptive fields of visually responsive neurons are spatiotemporal responses [DeAngelis et al 1995]. For retinal ganglion cells and lateral geniculate neurons, the receptive field in circular centre-surround with either ON-centre or OFF-centre sensitivity. The six-layered lateral geniculate nucleus receives inputs from different eyes to alternating layers. From there, lateral geniculate nucleus axons fan out to V1 of the visual cortex (area 17). However, only about 10% of the synaptic inputs to the lateral geniculate nucleus originate from the retina – some 30% originate as excitatory synapses from the visual cortex with additional inputs from the midbrain and brainstem [Derrington ?]. Almost all optic tract axons synapse in the lateral geniculate nucleus, a few branching off to the superior colliculi and pretectal area of the midbrain which passes to the Edinger-Westphal nuclei through the 3rd nerve to mediate the pupillary light reflex.

Most of the neurons of the macaque monkey primary visual cortex (striate cortex area 17) respond to specifically oriented line segments [Hubel & Wiesel 1977]. In layer IVc almost all cells have circular symmetry and are monocular while above and below layer IVc most are orientation specific (some vertical, some horizontal and others oblique) of which half are binocular. Cells of like orientation are grouped into narrow columns ~0.4 mm in cross sectional width (ocular dominance columns) with adjacent columns involving small shifts of orientation – a 1-2 mm traverse in any direction traverses through one or more 180° rotations. A full set of columns for a complete 180°

rotation comprises a hypercolumn of width 1-2mm which are unconnected to other hypercolumns. Complex (binocular) and simple (monocular) hypercolumns are found in layers II, III, V and VI while simple cells in layer IVb are simple and are predominantly monocular. Most human areas of the visual cortex are similar to those of the macaque including two distinct processing streams (parietal dorsal pathway for processing visual motion and temporal ventral pathway for processing colour and form) in both cortices [Tootell et al 1996, Gegenfurter & Hawken 1996]. The neural substrate for motion detection resides in the middle temporal area (MT or V5) based on directionally selective neurons – this is critical in the generation of smooth pursuit signals. Such directional selectivity is enabled through nonlinear combinations of simple receptive field neurons which exhibit temporal phase shift lag of the surround to centre response [DeAngelis et al 1995]. Advanced mammals have a wide range of up to 20-30 different cortical visual areas, yet all mammals including insectivores, marsupials and monotremes possess a primary visual cortex V1 [Rosa & Krubitzer 1999]. Visual area V2 occurs in most eutherians and is distinguished by its principal thalamic input from the pulvinar complex rather than the lateral geniculate nucleus. The pulvinar nucei of the thalamus in higher mammals is proportionately larger especially in primates. The pulvinar nuclei of the thalamus are divided into oral (somatosensory), superior and inferior (both visual) and medial (visual and multisensory) divisions [Grieve et al 2000]. They have reciprocal connections to large areas of the cerebral cortex including the visual cortex and is implicated in the function of visuomotor tasks such as saccadic and smooth pursuit movements of the eye.

Multiple layer parallel feedforward networks with Hebb-type synaptic weight modification can generate the major features of the mammalian primary visual cortex. Linsker (1986) used the Hebbian learning rule to model the formation of receptive fields in the early stages of visual processing through a layered network of limited connectivity. As learning ensues, the lower layer units develop on-centre and off-centre receptive fields resembling the receptive fields of ganglion cells in the retina. Elongated receptive fields develop in the upper layers that resemble simple receptive fields of the visual cortex. Feature analysing centre-surround cell and orientation-selective cell layers can emerge through self-organisation and become progressively organised in orientation columns through the network under random weight inputs, ie. without environmental input to the network [Linsker 1986 a,b,c]. Layer A comprised photoreceptor cells, Layer B of retinal cells, Layers C to f represented circularly symmetric cells (retinal ganglion) and layer G represented orientation-specific cells of the primary cortex. When connected with excitatory lateral connections, layer G yielded columnar registration of its orientation-specific cells.

The lateral geniculate nuclei and cortical stream through V1 and V2 generate context-sensitive perceptual groupings (which aid segregation of objects from the background) from visual inputs [Grossberg et al 1997].

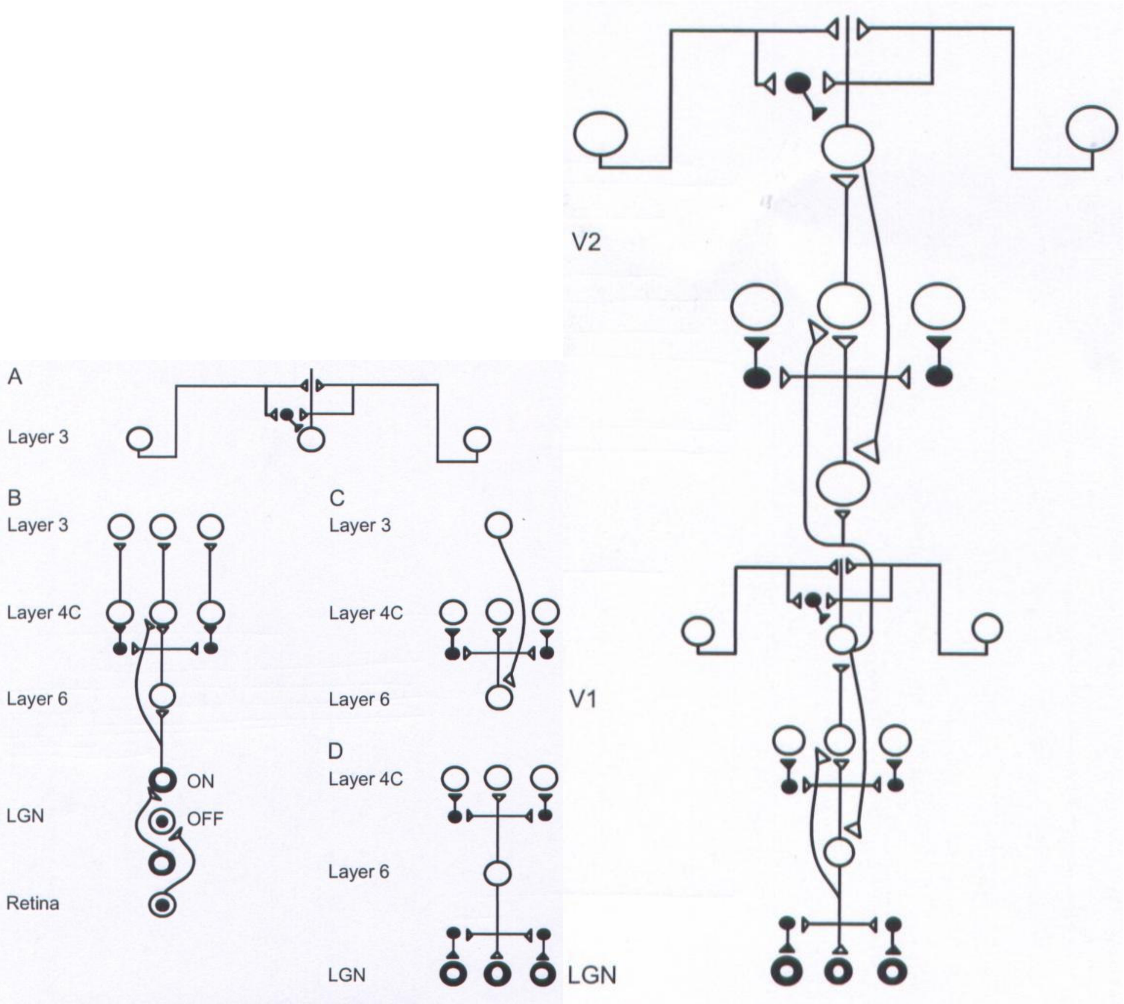


Fig D-10 (a) Model of retinal, V1 and lateral geniculate nucleus neurons; (b) Model of LGN-V1-V2 circuitry [from Grossberg et al 1997]

Activation of regions of the visual cortex suggest that many neurons are involved in the representation of objects against the notion of a few specialised "grandmother" cells. Context-sensitivity is indicated by the Kanizsa squares which imply cooperative processes which build a coherent boundary due to cellular responses in V2 through long range centre surround excitation/inhibition.

Nitric oxide (NO) is a short-lived signalling molecule generated from L-arginine by Ca^{2+} calmodulin-stimulated enzyme NO synthase mediating increased cGMP levels that occur on activation of NDMA receptors. The brain has the highest levels of nitric oxide synthase than any other organ. NO diffuses from its production site through cell membranes and has a sphere of influence of 200 μm from a point origin which can enclose 2 million synapses. In the visual system, NO is produced by both postsynaptic and presynaptic neurons and acts as a neurotransmitter which diffuses through cell membranes to act on neighbouring cells from the retina through the thalamus to the cerebral cortex [Cudeiro & Rivadulla 1999].

The main communication paths of the brain are inherited genetically according to a general architecture. The primary pathways are the thalamocortical visual pathways to the visual cortex and the descending pyramidal pathway from the motor cortex. The spinothalamic tract from secondary somatic sensory neurons ascend to a number of destinations. Only a small fraction reach the ventral nuclei of the thalamus, from where axons ascend to somatic-sensory cortex, ie. only two synaptic interruptions to maintain the toipography of sensory periphery. The other destination of the spinothalamic tract includes interruption at the rhomboencephalic neurons on the way to the thalamus to incorporate input from the auditory system.

SENSORIMOTOR PATHWAYS

Preprogrammed automtic behaviour is characterised by information flow from the cerebellum to the thalamus on to the motor cortex. The thalamus relays to the motor cortex signals from the basal ganglia which initiates movement. All voluntary movement begins in the motor cortex which comprises large pyramidal cells. Such cells have very long axons that connect to the root of the spinal cord resulting in muscle constriction. In addition, it receives feedback from the muscles and joints. Voluntary movement requires sensory feedback analysis from the post central sensory cortex. Spatial analysis for goal orientation is performed in the tertiary parts of the parieto-occipital regions of the cortex. The premotor cortex is responsible for sequential scheduling of the separate elements of motor activity. The prefrontal lobes provide the intentions and goals to guide motor behaviour. The pyramidal system comprises descending fibres of the motor cortex which cross to the opposite side and terminate in a distributed fashion to the voluntary nuclei of the cranial nerves and the spinal cord. The number of fibres of the corticospinal tract decrease down the spinal cord as they terminate. Peripheral nerves fibres thence are distributed from the spinal cord to the striated muscles, each innervating ~100-300 separate muscle fibres. Skeletal muscles are innervated by alpha motor neurons. Muscles have proprioceptive sensors (muscle spindles, Golgi tendon organs, joint receptors) for monitoring and controlling motor activity. Reflexes involve afferent fibres directly synapsing onto efferent fibres across the spinal cord while bypassing the brain. In the stretch reflex, muscle stretch causes the discharge of impulses in its neuro-muscular spindles. Afferent fibres pass to the spinal cord and synapse directly onto efferent fibres which conduct impulses from the spinal cord to the motor endplates of the muscle fibres which increase muscular tension. The spinal cord possesses afferent fibres for proprioceptive and tactile information to be passed from the muscles, tendons, ligaments and joints to the brain. They follow three divergent routes:

(i) direct to the lower motor neurons for reflex arcing;
(ii) fibres to the spinal cord to relay to the cerebellar cortex (spinocerebellar tract);
(iii) fibres to the spinal cord to the medulla and thalamus and then to the somatosensory cortex.

Sensory feedback is provided by the proprioceptive sensors in the muscles, joints and skin while exteroceptive sensors provide direct observation feedback (vision, etc). Reafferent connections allow comparison between command and actual performance for control. Proprioceptive awareness of the body is central to controlling the agent in relation to the outside world – it may even be central toconsciousness in representing the agent in relation to the world. The body image is used to predict and control the outcomes of behaviour. The self-model provides a reference frame from which to integrate sensorimotor transformations. Tactile sensibility is provided by two different sensors:

(i) simple touch for crude localisation;
(ii) tactile discriminators to determine pressure, fine localisation, and size/shape perception.

Tactile discrimination data follows the same pathway as proprioception. Simple touch passes through the spinal cord through the spinothalamic tract to the thalamus, from which thalamocortical fibres relay the signal to the postcentral gyrus of the parietal cortex. Pain sensors are naked terminals of the branching nerve network – they enter the spinal cord and fibres of the lateral spinothalamic tract convey the signals directly to the thalamus (where pain recognition occurs). Thalamocortical fibres relay these signals to the postcentral gyrus of the parietal cortex (for integration with other sensory stimuli). Cold receptors and warm receptors which are distributed across all body surfaces both follow the same pathway as pain. Sensory pathways separate into pain and temperature fibres and position and touch fibres after entering the spinal cord through the dorsal root. Both sets of fibres reach the lower medulla, and then onto the thalamus with pain pathways being very extensive.

The motor system comprises the upper motor pathway, lower motor neuron, myoneural junction and muscle. The upper motor neuron pathway begins in the precentral gyrus. The pyramidal tract descends from the precentral gyrus, some of the fibres passing into the midbrain, pons and upper medulla. In the lower medulla, the pyramidal tract passes from the brain stem to the spinal cord. The lower motor neuron is final pathway to muscle. The arrival of the motor neuron at the neuro-muscular junction causes the release of acetylcholine which crosses the nerve/muscle cleft and becomes attached to the acetylcholine receptor in the motor endplate. This causes depolarisation and muscular contraction. Cholinesterase destroys the acetlycholine and the muscle repolarises. Coordination deends on the smooth contraction of one group of muscles (agonist) and equally smooth relaxation of opposing muscles (antagonist).

Autonomic nervous system comprises the sympathetic and parasympathetic parts. The sympathetic nerves release adrenaline and noradrenaline, while the parasympathetic nerves release acetylcholine. Both work antagonistic actions on the smooth muscle, cardiac muscle and glands, including the lungs, stomach and intestines. Sympathetic nerves supply vaso-constrictor fibres to all blood vessels (except arteries supplying the myocardium). The parasympathetic nervous system supplies the secreting glands. The vagus nerve contain numerous afferent fibres from pressure and pH fibres. Parasympathetic fibres from the brain antagonise the effects of the sympathetic nervous system.

Preprogrammed automatic behaviour is characterised by information flow from the cerebellum to the thalamus and then onto the motor cortex. The hypothalamus at the base of the forebrain controls and regulates the activities of the autonomous nervous system (ie. the visceral system) and invokes emergency reactions to stimuli. The hypothalamus possesses a glandular appendage – the pituitary complex. The hypothalamus maps either directly or mostly via the midbrain reticular formation onto the motor neurons of the spinal cord. The hypothalamus receives input from the spinothalamic tract via the mesencephalic reticular formation, and from the hippocampus and amygdala directly or via the septum – the hypothalamus monitors the internal state of the body and is affected by motivation. Short term regulation of the autonomous system (eg. the circulo-respiratory system) is controlled by the medulla oblongata. The thalamus relays the motor cortex signals from the basal ganglia which initiate movement. The basal ganglia is involved with the smooth coordination of movement. Voluntary movement is a function of the motor cortex which comprises large pyramidal cells. They have very long axons that connect to the root of the spinal cord resulting in the construction of muscle. In addition, it receives feedback from the muscles and joints. Voluntary movement requires sensory feedback analysis from the post-central sensory cortex. Spatial analysis for goal orientation is performed in the tertiary parts of the parieto-occipital region of the cortex. The premotor cortex is responsible for sequential scheduling of the separate elements of motor activity. The prefrontal lobes provide the intentions and goals to guide motor behaviour. Descending systems originate in the forebrain. The neocortex which is the major part of the human cerebrum contains 70% of the neurons of the human brain – it appears to form internal representations of classes of objects in symbolic form and is capable of extrapolating to future events. All areas of the neocortex project to the corpus striatum. The somatosensory, visual, auditory, and motor cortex project into different regions of the striatum. From the striatum, there is a massive projection into the global pallidis of the corpus striatum in a funnelling arrangement. From the globus pallidus, the ansa lenticularis fibre bundle divides into two: part curves back on itself into the forward portion of the ventral nucleus of the thalamus in a feedback loop while the rest of the ansa lenticularis bundle projects to the reticular formation of the midbrain. The corpus striatum is important in bodily movement in channelling impulses to the motor neurons - the corpus striatum sends projections to the reticular formation which acts on motor neurons. It also receives projections from the cerebellum via brainstem connections which also send fibres to the motor cortex. Projections from the neocortex reach a wide range of structures – striatum, thalamus, midbrain structures (superior collicus, red nucleus, midbrain reticular formation), pons of the hindbrain, and the spinal cord directly. Around 5% of corticospinal fibres from the motor cortex specifically synapse directly to motor neurons which innerevate the muscles of the extremities, providing a short cut from the motor cortex to motor neurons. The autonomic nervous system innervates the glands and smooth musculature of the viscera. All glands are essentially tube structures coated with smooth muscle. Motor innervation of this muscle originates from the first neuron in the central nervous system which projects its axon into the secondary neuron in the peripheral ganglion which in turn projects its axon to visceral muscle tissue. The autonomic system is controlled from the hypothalamus which monitoirs the state of internal tissues and organs. Pathways descending to the autonomic motor neurons are interrupted at numerous levels for further processing to ensure that no single excitatrion influences visceral function unduly. The input to the hypothalamus is from the midbrain reticular formation. This receives input from the hippocampus and amygdala of the cerebrum, the two principal components of the limbic system concerned with affect and emotion. It is closely connected to the hypothalamus and receives input from the perceptual areas of the cortex. The hippocampus receives input from all parts of the cerebral cortex through a series of intermediate neocortical fibres. There exists a suspected reverberatory circuit along the hippocampus-fornix-thalamus-cortex pathway. Inputs to the hypothalamus also derives from the midbrain reticular formation and frontal cortex. The amygdala receives input specifically from the neocortex from the primary sensory field. Both parts of the limbic system receive input fibres from the olfactory cortex – olfaction was bthe earliest sense and provides fundamental discrimination of biologically-important objects at a distance. The pons receives massive projections from all parts of the neocortex and sends maasive projections to the cerebellum. The spino-cerebellar tract from secondary sensory neurons of the hindbrain-spinal cord ascend to the cerebellum.

MEMORY SYSTEMS

Mammals have two different types of memory which use two different brain structures for encoding information. The brainstem is associated with reflex behaviour and lower level learning. Memory traces in the human brain are localised to the cerebellum, hippocampus, amygdala and cerebral cortex. Working memory is associated with the prefontal cortex, particularly the principle sulcus, which accesses relevant stored information in the cerebral cortex – working memory provides moment-to-moment awareness and retrieves rchived information (similar to a "blackboard"). Long term memory storage occurs in the cerebral cortex which is also the region responsible for higher cognitive processes in mammals. The temporal lobes on the inner surface of the underside including the hippocampus are responsible for the storage of new long term memories. The hippocampus comprises of pyramidal cells and lies in the temporal lobe of the cerebrum and is the origin of working memory. The hippocampus is associated with semantic/episodic information storage. Procedural knowledge is learned by repetition and is associated with the cerebellum – it is learned by Hebb's rule through association between presynaptic and postsynaptic activity. Declarative knowledge involves association of simultaneous stimuli about single events whereas procedural knowledge involves the association of related sequential stimuli. Declarative knowledge is learned by altering the connection strength between presynaptic activity and a third modulatopry neuron without post synaptic activity. The hippocampus is the temporary store with a characteristic timescale of weeks or months prior to transfer to the permanent store of the cerebral cortex [Kandel et al 1992]. It has a regular structure and its principal region comprises a sheet of output neurons or pyramidal cells with interneurons of mostly stellate neurons. Pyramidal cells are analogous to Purkinje cells and interneurons are analogous to granule, Golgi, basket and stellate cells in the cerebellum. Hence, it is an associative memory like the cerebellum. The hippocampus learns its internal classification of input patterns for which it uses the granule cells with modifiable synapses. The hippocampus appears to be responsible for spatial memory of objects in the environment. It participates in the formation and retrieval of semantic memory and the cerebral cortex is associated with storage [Lynch & Baudry 1984]. In fact, the neocortex as a whole operates similarly to the hippocampus the neocortex comprises 70% of all the neurons of the human brain. The neocortex is dominated by pyramidal and stellate cells. Neocortical nets form internal representations of classes of objects with climbing fibres activating the classification process through long term potentiation. Memory is characterised by long term potentiation or persistent postsynaptic potentials following cortical and hippocampal activity. Objects are represented in memory by association of rhythmic and synchronised firing which bind activity in different parts of the cortex. The striate cortex (primary visual) cortex is essential for learning and memory of visual patterns. There is an area on both sides of the cerebral cortex – the inferior temporal sulcus - but dominant in the right hemisphere which is concerned with the recognition of faces. This region lies on the underside of both occipital lobes extending forward to the inner surface of the temporal lobes. The reason for such a highly specialised function being donated such a large region of the brain is that recognition of individuals lies at the heart of human sociability.

The human memory system comprises two distinct systems: episodic and semantic. Semantic memory encodes our knowledge about the world. The hippocampus plays a critical role in the encoding and retrieval of episodic memories and involves long term potentiation [Shastri 2002]. Episodic memory refers to the remembrance of specific events and situations. Remembering allows us to re-experience stored personal events. The acquisition of those memories is enabled by the hippocampus. Patients with Korsakov syndrome due to lesioned hippocampus are unable to acquire new episodic memories but their ability to acquire semantic and procedural knowledge is retained. Episodic memory provides the basis for conscious experience as a stream of personal events and situations. This provides for an individual's awareness of his/her existence and identity extending through a personal past – this provides the ability for mental time travel. The hippocampus acts as an auto-associative memory implemented within the recurrent connections of CA3. This also acts as a conjunctive code that binds together different items into a relational memory. The relational structure enables entities (giver, recipient, object, location, temporal-location, etc) occurring during the event to certain roles within the event and are distinguished from roles within other events. Events occur over spatial and temporal extents, are emotionally charged, and invoke a rich sensory texture. Event understanding requires the activation of a complex web of conceptual knowledge (including semantic knowledge, causal knowledge of cause-and-effect, and schematic embodied representations of generic actions) yet the brain can reconstruct an event from a small number of partial cues. Remembering a past event requires retrieval of the information from episodic memory. A retrieval cue activates a memory trace which provides for reconstruction of the episode. This reconstruction through a small number of role-entity bindings constitute the event's episodic memory trace encoded in the hippocampus. During recall, the event's episodic memory trace activates the event recall from the cortex (especially the perirhinal cortex) including sensorimotor relational schemas (encoded within the parahippocampal cortex) and semantic and other knowledge (from the parietal and prefrontal cortex which project to the parahippocampal cortex). High level outputs from multiple cortical areas such as visual attributes and features, spatial configurations, etc are directed into the medial temporal lobe and its associated structures (perirhinal, entorhinal and parahippocampal cortices). However, memory is not always accurate as the encoding process can support false memory – strong visual imagery at encoding promotes the retrieval of perceptual detail that can lead to false episodic memories [Paller & Wagner 2002]. The frontal cortex as well as the medial temporal regions is implicated in the formation of episodic memories [Buckner et al 2000]. Episodic encoding correlates with activity in the border at the motor and premotor cortex along the inferior frontal gyrus near Brodmann's areas 44, 6, 44, 45 and 47. The dorsal region (areas 44 and 6) of the left cortex plays a role in phonological processing while the inferior regions (areas 44, 45 and 47) play a role in semantic processing. Episodic memory also provides the basis for pre-experiencing of future events by projecting personal events into the future but requires significant input from the prefrontal cortex (Brodmann's areas 9, 10 and 46) [Atance & O'Neill 2001]. Such prospective memory involves three distinct processes – development of plans; remembering those plans; remembering to execute those plans at some specified point in time in the future. This provides for plans geared towards one's own specific actions rather than script-like routines. Children of 3 years are capable of understanding the future as distinct from the past and includes projections and predictions. Only by 4 years do children prefer larger delayed reward over smaller immediate ones. This is peculiarly human and acts as a driving force for human culture as primates are generally are solely present-oriented.

Working memory as a short-term temporary storage memory mechanism ~3s of limited capacity allows for the manipulation of information to support complex tasks such as language comprehension, etc [Miller 1956]. Attention is the process by which unwanted information is filtered out due to capacity limitations in working memory. Goal-directed saccades allow us to bring interesting visual targets to the fovea – this is an example of visual selective attention. However, cognitive attention is independent of eye fixation and has the characteristics of an adjustable spotlight. The cocktail party problem is the archetypal selective attention problem. Priming – when one stimulus affects the processing of another stimulus – provides the basis for selection of stimuli. This does not preclude bottom-up stimuli analysis of simple physical features of irrelevant stimuli (automatic processing) or top-down object-based semantic analysis of perceptual objects guided by active schemata (controlled processing) [Johnston & Dark 1986, Treisman & Gelade 1980, Shiffrin & Schneider 1977]. The Stroop effect defines a special kind of semantic interference fro, irrelevant stimuli – there is a latency in naming the colour of ink in which a word is printed when the word is the name of a different colour. Selective attention acts as an imperfect sensory filter which attenuates irrelevant stimuli but passes relevant information for further levels of analysis. Higher level biases as a result of top-down processing – priming – account for the divided attention aspects of the cocktail party problem [Broadbent 1982]. Working memory has four major components – an attentional control system and the central executive (resident within the frontal cortex), aided by the phonological loop to hold verbal information through articulatory rehearsal (resident in left Brodmann's areas 40 and 44) and the visuospatial sketchpad to hold visual, spatial and kinaesthetic information (resident in right Brodmann's areas 6, 19, 40 and 47). In addition, a back-up store supporting series recall, chunking of information, and the integration of linguistic and visual data is necessary. This role is performed by the episodic buffer, a temporary memory of limited capacity capable of integrating information from multiple modes [Baddeley 2000]. It is episodic in that it holds episodes which integrate information. It is controlled from the central executive which retrieves information through conscious awareness.

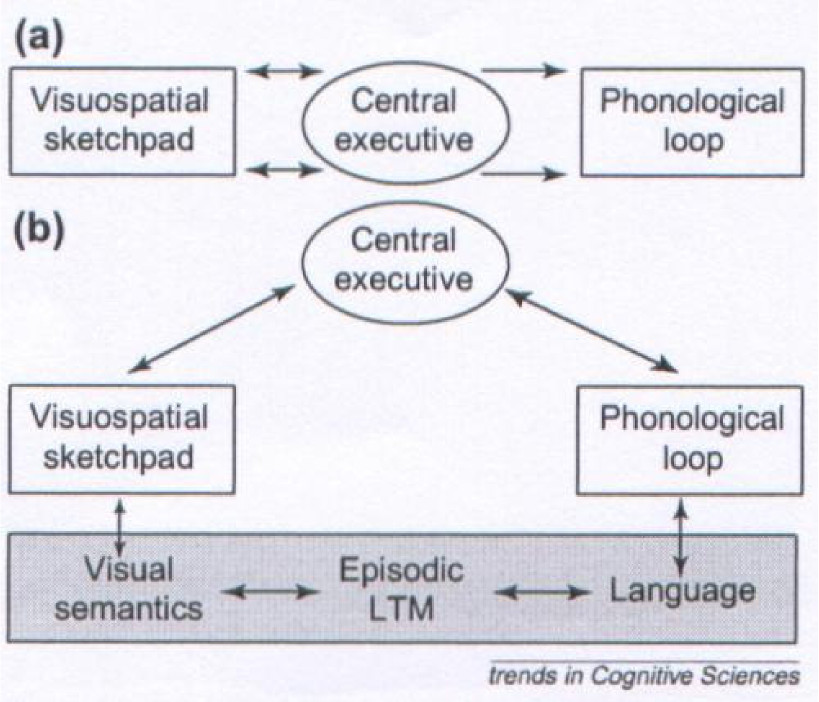


Fig D-11 Working memory structure [from Baddeley 2000]

Appendix E: Space Medicine

There are a number of medical effects on the human body imposed by manned spaceflight. Human physiology is based on multiple homeostatic feedback systems, the major ones being the cardiovascular system, the respiratory system, the digestive system, the excretory system, the nervous system and the endocrine system. Blood is the main transport system of the body which supplies the cells with nutrients and removes waste products. Blood is pumped around the body by the heart which comprises of two pumps. The left side pumps oxygenated blood through the aorta and arteries to the tissues while deoxygenated blood returns through the veins to the right side which pumps blood through the pulmonary artery to the lungs. Oxygenated blood returns to the left side of the heart through the pulmonary vein from the lungs. A man of 70kg has 5litres of blood which is circulated in its entirety around the body once per minute. Oxygen is absorbed from the air in the lungs by the blood as it passes through the lungs for transport to the tissues. Waste carbon dioxide is produced by the tissues and is offloaded at the lungs by blood for expulsion. Nutrients are ingested through the gastric system for the production of energy and growth of tissue. Enzymes in the digestive tract break down large molecules of food which is absorbed into the blood for transport via the portal vein and liver to the tissues. Undigested food is expelled via the rectum. Waste products of cells except carbon dioxide are excreted from the body in solution via the kidneys and urethra. There are two global control systems in the human body - the nervous system and the endocrine system. The endocrine system controls the functions of the organs through the secretion of chemical hormones from the endocrine glands. They play a major role in the reproductive system. The nervous system exerts control of the muscles through electrical impulses from the brain through the spinal cord. Feedback is provided back to the brain from the sense organs - skin (touch, pain, temperature) and the special senses (sight, smell, hearing and taste).

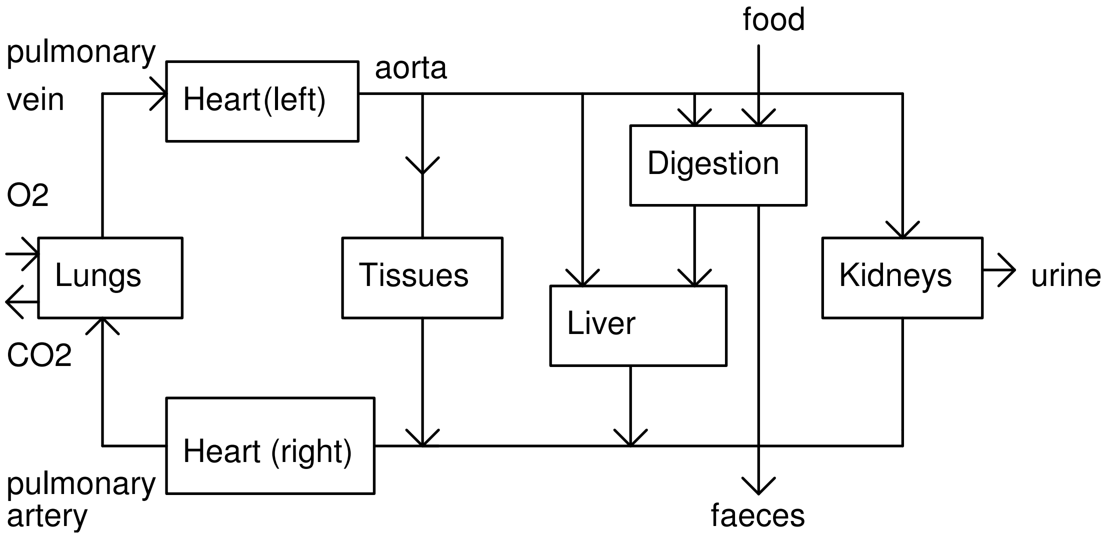


Fig E-1 Simplified schematic of the major physiological subsystem loops of the human body

Most physiological effects of spaceflight on the human body return to normal within 4-6 weeks postflight. The radiation environment poses a hazard to personnel against which shielding is required imposing additional structural mass to spacecraft. Sublethal exposure can generate genetic defects and the production of tumours or leukemia. When ionising radiation strikes a cell, it may damage it. As well as breaking DNA strands, ionising radiations leave a trail of ionised water molecules and reactive OH- ions. If DNA is not repaired, any damage will be passed on to daughter cells which may eventually result in uncontrolled growth, ie. cancer. This is especially the case in cells which divide regularly, ie. stem cells in bone marrow which produce red and white blood cells, the gastro-intestinal tract lining, and reproductive sperm cells. Other organs have lower but significant sensitivity to radiation such as epithelial tissue. High LET radiation such as neutrons cause double DNA strand breakage which has a radiation weighting factor of 5-20 (cf gamma and X-rays of 1). Half of the breaks are repaired within minutes, less than 10% are repaired after a few hours. Misrepairs cause mutation and cancers and occur to 0.03-0.2% of repairs depending on the impinging radiation LET. Fragments of DNA can be released from lethally irradiated cells which can be incorporated in sub-lethally irradiated cells undergoing DNA repair which can cause uncontrolled protein synthesis and cell proliferation. Radiation dose is cumulative over lifetime with effects becoming more severe with increased dose. The clinical effects of radiation poisoning are diarrhoea and nausea due to intestinal disorder, anaemia and haemorrhaging due to marrow suppression, infection susceptibility due to reduced white blood cell count, and infertility due to sperm damage. These occur due to the destruction of DNA integrity in rapidly dividing cells of the body. A 10-15 rad dose has no effect even after prolonged exposure but a dose of 40-100 rad causes vomiting and nausea in 5-10% of people but no serious disability. A dose of 100-200 rad causes vomiting and nausea in 25-50% of people but no deaths. A total whole body dose of 200 rad is sufficient to cause tissue damage and deaths begin to occur within 2-6 weeks of exposure from radiation sickness. A dose of 200-350 rad will cause 20% of people exposed to die, 50% at 350-550 rad, 100% at 550-750 rad. On Earth, the average annual background dose is 200 mrad/y but in space it is much higher at 20-40 mrad/day. In LEO, most radiation exposure is due to galactic cosmic rays and the South Atlantic anomaly. The South Atlantic anomaly is variable but can give up to 100 rad/hour. In higher orbits, solar proton events such as solar flares become greater potential hazards. Galactic cosmic rays yield annual doses of around 15 rad (1Sv = 100 rad) similar to a stomach X-ray. The primary problem is solar flares which occur some 5 to 10 times per year, each producing between 10 and 1000 rad/hour environments. Around 400 rad is sufficient to kill 50% of the exposed humans within 30 days. Above 1000 rad, death occurs within days or even hours rather than weeks. Anti-radiation drugs which generally reduce tissue exposure to oxygen may offer some protection against moderate doses, eg. antioxidants (glutathione, vitamin E), aliphatic alcohols, dimethyl sulphoxide. The astronaut radiation dose limit is presently 50 rem for bone marrow and only extended planetary missions exceed this. Over short periods, NASA's current limit for blood forming organs are <25 rad for 30 days, <50 rad for one year, and <400 rad for the entire astronaut career. This level increases the risk of cancer by 3%. However, even low levels of exposure may cause radiation induced genetic instability resulting in mutated genes after several short missions.

There are a number of general physiological effects due to medium term exposure to weightlessness referred to collectively as Space Adaptation Syndrome [Leach et al 1990]. The most prominent of these is bone demineralisation. There are additional difficulties which occur when the body must re-adapt to Earth gravity conditions at the end of a mission. The neurovestibular apparatus of the inner ear provides sensory data to the brain concerning head movements necessary for maintaining balance of the body and visual fixation. The neurovestibular system is concerned primarily with the maintenance of equilibrium and spatial orientation of the body by the integration of visual information from the environment, proprioceptive information from the muscles and joints, and vestibular (balance and motion) information from the inner ear. The human body resembles a multi-link inverted pendulum with rotational movement at the ankle, knees, hip and neck – an open chain linkage mechanism of four rigid links (lower leg, upper leg, torso and head). The body compensates for disturbances to balance and motion sensing in the cavities of the inner ear comprise two types of senses: (i) otolith organs sense linear forces of the head in all three directions (including gravity); (ii) semi-circular canals sense rotary movements of the head in three planes. The otolith generates signals combining translational head movements with attitude head motions from the vertical which must be subtracted out using information from the semicircular canals in the vestibular nuclei. All the sensory information is processed by regions of the mid-brain, cerebellum and cerebral cortex and integrated with visual and somatosensory data. In this way, spatial orientation of the body relative to an external reference frame is maintained to enable accurate motor commands to be executed by the muscles in a coordinated manner. The vestibulo-ocular reflex provides eye movement to maintain stable gaze during head movements and it is dependent on otolith signals, eg. ocular counter-rolling during head tilting. Sustained head rotation requires the use of the optokinetic feedback loop to maintain compensatory eye movements for stable retinal images once the inner ear signals fade. If head motion exceeds 20^o, an involuntary jerky saccade flick of 0.1s duration corrects the eye position at the end of its orbit to the centre of the eye socket.

The bony labyrinth of the inner ear lies in the temporal bone, the hardest bone of the body. It is filled with perilymph fluid identical to cerebrospinal fluid with a high concentration of Na ions but low in K ions. Within the perilymph the bony labyrinth is suspended by membranous labyrinth connected by tissue fibres. It is filled with endolymph fluid similar to intracellular fluid with high concentrations of K ions but low in Na ions. Posterior superior part of the membranous perilymph is the vestibular part distinct from the anterior inferior auditory cochlear duct. The vestibular apparatus comprises of three perpendicular semicircular canals within each of which the wider ampulla contains a patch of sensory hair cells (crista ampullaris) similar to actin microfilament impregnated microvilli. Each hair cell has general stereocilia bundles. All three semicircular canals are connected to two connected vestibular sacs, the utriculus and saccule both of which contains a patch of sensory hair cells, the macula. The stereocilia are mechanoreceptive transducers which when bent in a given direction, open K channels allowing K ionic current to flow from endolymph into the hair cells which affect Ca metabolism of the cell and release neurotransmitters to propagate action potentials along the vestibular division of the VIII cranial nerve to the brain. The maculae of the utricle and saccule are embedded in the otolithic membrane, a gelatinous structure containing numerous small $CaCO_3$ crystals to provide inertia. The otolithic membrane responds to both linear acceleration and angular acceleration of the head while the crista ampulleris responds only to linear acceleration as they do not contain otolithic crystals. The vestibular nerve enters the brainstem at the cerebellopontine angle. Most of the fibres synapse on the neurons of the vestibular nuclei within the medulla and pontine tegmentum which project to and receive from the flocculonodular node of the cerebellar cortex (for balance) and motor nuclei of the cranial nerves VI, IV and III ocular muscles (for eye movement) in VOR (responsible for gaze stability). They also project into the upper cervical region of the spinal cord for vetibulocollic reflex involving moving the head in relation to the body, the lower motor neurons of the spine which innervate the limbs for vestibulospinal reflex involving posture. It also projects to the thalamic nucleus close to the ventral posterior complex which receives somathalic information. The thalamic nucleus projects up to the postcentral gyrus of the cerebral cortex. However, it is the only sensory modality which is reflexive and does not involve thalamic or cerebral processing. The pontine reticular formation integrates vestibular acceleration data to give position. When the head is turned, the environment sweeps across the retina, and this visual information is input to the 8th nerve, so the vestibular nuclei algebraically scans the velocity signals from vestibular nerve and visual pathway. If there is a mismatch, vertigo results. The cerebellum is central to correction of malfunctions of the vestibular system. The cerecellum receives input from the visual system via the olivary tract enabling it to monitor vestibular induced motor performance. An inhibitory pathway from the cerebellum to the vestibular nuclei acts to alter the transmission of neural signals from the vestibular system to the extra-ocular muscles. Vestibulo-spinal postural reflex plays an important role in the maintenance of bipedal posture within the gravity field. It is mediated by push-pull balance between extensor and flexor skeletal muscles of the neck, trunk and extremities.

On Earth, eye, head and body motions are interpreted relative to the Earth's gravity vector, but in space no fixed gravity vector is apparent – indeed, voluntary pointing accuracy and static limb position are impaired under weightless conditions. When environmental conditions change, the nervous system interprets sensory data differently. In space, the operation of the otolith organs are altered but that of the semicircular canals is unaffected. Otolith organs no longer give the static head position with respect to gravity and vision becomes increasingly dominant. The brain then interprets otolith signals as arising from translation movement only. Prior to adaptation, head tilting is perceived as a linear backward movement. Vestibulo-ocular reflex in the pitch and roll planes differ in space from Earth due to changes in otolith function. The otolith also influences the optokinetic system when eye movements are in the vertical plane – they tend to rotate the eyeballs to compensate for the downward pull of gravity (absent in weightlessness). Around 2/3 of all astronauts suffer from degrees of space motion sickness with its attendent symptoms of nausea for the first few days of spaceflight. It derives from a conflict between neurosensory inputs from visual sensors and vestibular organs of the inner ear until the body adjusts its motor programs for the weightlessness conditions. Antihistamines diminish the liability to motion sickness. Treatment with scopolamine and dexedrine alleviates the symptoms somewhat. For a short period of the order of days (typically 3 days), the human body undergoes adaptation to the weightless environment. These involve neurosensory disturbances culminating in space motion sickness which affects around 53% of astronauts over this period, and disorientation is common. It can cause intense nausea, gastro-intestinal discomfort, loss of appetite, general malaise and lethargy resulting in decreased performance levels particularly in demanding tasks. Over this period, a new set of physiological parameters are being established. The vestibular organs of the inner ear are the sensory organs which provide the central nervous system with information about head movements - both linear acceleration of the head and angular orientation of the head with respect to the gravity vector. The semicircular canals comprise of 3 mutually perpendicular fliud-filled tubes containing hair cells and the otoliths are two sacs filled with calcium carbonate crystals embedded in a gel. In space, there is a mismatch between the information provided by the semicircular canals which measure head orientation only and the otoliths which measure a combination of linear movement and orientation changes with respect to the vertical gravity vector. The otolith organs do not experience change in attitude of the head in pitch and roll movements as they do in a 1g environment. A lack of proprioceptive normality occurs due to a lack of normal posture in zero gravity. Mechanical receptors in the muscles and joints provide proprioceptive feedback on posture. The normal action of all of these sensors are disrupted which conflict with previous experience in a 1g environment. The brain integrates signals from different sensors. Visual references provide external cues to the body which conflict with the other sensory input data generating neural mismatch. Such neural mismatch due to sensory disorientation causes vertigo. Moving visual stimuli often induces the illusory sensation of self-motion with illusions being common (vertigo). The body eventually learns the new stimuli-motor responses appropriate to zero-gravity over this period involving the adaptation of the vestibular-ocular response reflex which stabilises gaze during head movements. Some pre-flight adaptation is possible to alleviate some of these effects such as stemetil, valium, scopolamine or stugeron. Cawthorne-Cooksey physiotherapeutic exercises which involve head and eye movements to encourage dominance of vision over other sensory cues.

Marangoni convection is a capillary effect determined by surface tension. The main contribution to heat transfer in fluids under microgravity is due to Marangoni convection which occurs when Marangoni convection heat flow exceeds the thermal conductivity capacity of the fluid [Chuen & West 1978]. In this case, the effects of temperature differences affect surface tension as heating decreases surface tension – Marangoni convection is a thermo-capillary effect caused by surface tension at the liquid /gas interface in the presence of a thermal gradient. Surface tension minimises the surface area-to-volume ratio of the liquid by adopting a spherical shape. It moves from hot to cold regions as the interface drives the motion of the fluid such that bubbles grow rapidly with a few stable large bubbles which do not disperse through the liquid. Hotter regions of the liquid tend to spread at the expense of the cooler surface areas, thereby driving mass cellular convection within hexagonal cells.

The musculo-skeletal system experiences reduced gravitational loading particularly the thighs, legs and axial skeleton as the neutral body posture assumes a foetal position. Upright posture on Earth causes compressional gravity forces along the spine which is absent in space. An average 1.75m tall astronaut may exhibit a height increase of 4cm due to decompression of the vertebral disks. Due to the zero-gravity environment, the weight bearing muscles atrophy. There is a significant decrease in cross sectional area of the skeletal muscle after 11 days in space (25-30% in 30 days) in conjunction with a decrease in the number of capillaries per muscle fibre. Muscle volume loss results in loss of strength, particularly in the abdomen, the extensors of the back and neck, the gluteal muscles and the quadrupeds (extensors of the lower limbs), ie. those that contribute most to posture, locomotion and neuromuscular coordination. Urine analysis of astronauts indicate increases in the excretion of N, Na, Mg, K, phosphates and almost all amino acids indicative of muscle loss. Auto-antibodies for muscle degradation have also been found in serum samples.

Around 60% of the human body weight is water. The distribution of body fluid is altered in space with 1.8 litres of fluid being displaced from the legs to the upper body and subsequently lost by excretion. Initially in space, the face, neck and head are engorged and the sinuses are congested affecting sight, hearing, smell and taste. The body responds as if the total blood volume has been increased, so that the total blood volume and body water volume decreases within 7-10 days of the flight by 10-15%. Hormonal control in conjunction with kidney function which increases its filtration rate by 20% dictates this process through fluid volume and electrolyte concentration data. Space sickness probably contributes to this fluid loss. The effect of blood volume alteration is not clinically important but such effects probably contribute to the occurrence of cardiac arrythmias in space due to increased cardiac output (increased and premature atrial and ventricular beats). Due to the decreased blood volume, red blood cell mass decreases by 10-20% peaking at 60 days inflight (space anaemia). This is not clinically significant unless traumatic blood loss occurs entailing the need for transfusion. On returning to Earth, the reduced blood volume causes postflight orthostatic intolerance - the inability to stand without fainting due to reduced venous return to the heart and a fall in blood pressure. Recovery of orthostatic tolerance typically takes 3 days on return to Earth. The blood volume and red blood cell count recovers to normal some 50-60 days after return to Earth. The musculo-skeletal systems also lacks strength and endurance exacerbated by the reduced red blood cell mass. The therapeutic effects of drugs is also affected due to body fluid distribution which affects all major organ functions. Regular exercise at around 2h/day, eg. treadmill, bicycle ergonometer or isometric exercise during spaceflight, adequate isotonic saline fluid intake and lower body negative pressure maintain normal cardiovascular function and maintain nitrogen balance [Nicogossian et al 1988]. Exercise alone however is insufficient for maintaining muscle mass but it does help retard muscle loss especially with the use of lower body negative pressure trousers. This device fits over the lower body to produce pressure on it and redistribute blood towards the legs. The Russian Penguin suit is a special elasticised suit which partially compensates for gravity by opposing movement of the legs and trunk but it is not totally effective for long-duration flights. Fluid distribution is not clinically significant otherwise. NaF as a mineral supplement offers some alleviating effects to muscle loss but it is regular exercise that prevents general deconditioning. The recovery of muscle mass typically takes 3-8 weeks.

Astronauts who spend more than 30 days in orbit show signs of alteration in bone composition which is not fully reversible in many ways similar to accelerated ageing during the flight [Taylor 1993]. Weightlessness causes changes in bone composition which apparently is not fully reversible. Increased hydroxyproline excretion indicates breakdown of collagen which comprises ~50% of bone. This is calcium loss from skeletal bone. Calcium is implicated in numerous physiological functions including muscle contraction and neurotransmitter release. It is also the most abundant intracellular messenger in cell metabolism. The human skeleton contains around 1 kg of Ca. High levels of glucocortisoids induced during the flight inhibit bone formation and increased bone resorption so that osteoblast activity is depressed - osteoblasts are bone cells that secrete the components of bone for bone growth. The effect on marrow formation may be the origin of red blood cell mass loss. Bone mineral metabolism is seriously affected during spaceflight in that Ca balance becomes negative throughout the flight. There is an increased concentration of Ca in the blood (hypercalcaemia). This is similar to the condition of osteomalacia where Ca salts fail to deposit in new bone causing structural weakness. Increased hydroxyproline excretion in astronaut urine samples indicates the breakdown of collagen which comprises ~50% of bone as collagen fibres. The mean Ca loss is ~50 mg/d over the first month which increases rapidly to ~200 mg/d by the second month rising more slowly thereafter. A Ca loss of 6% of total body Ca is typical over 3 months subsequently averaging 0.5-1.0%/month but the loss of Ca has not been observed to accumulate over 10%. A loss of 5% represents a dangerous tendency to osteoporosis and fracture. It is suggested that a one year flight results in a 27% loss of total body Ca, ie. ~300g. Calcium loss to weight bearing bones due to lack of mechanical loading and bone demineralisation can increase the risk of fracture due to increased brittleness and premature osteoporosis. High levels of glucocortisoids during flight causes inhibition of bone formation and increases bone reabsorption so that osteoblast activity is depressed.

The function of bone is to support the body composed of extracellular matrix of glycoproteins and collagen fibres with mineral component of Ca hydroxapatite crystals. Skeleton is 80% cortical bone and 20% trabecular bone. Cortical bone is predominant in long bones and on the exterior of all bones. It is solid and hard. Trabecular bone is spongey and occurs in the inner regions of bones to allow passage of marrow and red blood cells. It has high metabolic activity through marrow formation. This may be the origin of lost red blood cell mass content. Bone is continuously formed and resorbed by metabolic activity controlled by bone cells. Orthoblasts are miniature bone cells which secrete organic components of bone for bone growth while osteoclasts are cells which secrete digestive lysosome enzymes for dissolution of bone. Homeostasis maintains bone mass constant but as the body ages, bone resorption gradually exceeds bone growth (osteoporosis). Bone fluid within this osteocytic membrane over all bone surfaces contains some 500mg of Ca in equilibrium, ie. 0.05% of total bone Ca. Plasma Ca concentration controls bone cell activity as well as indirect control by hormones especially parathyroid and calcitonin. Normal dietary intake is 1000 mg/day to maintain plasma Ca concentration at 2.6 mmol/l. When plasma Ca levels fall, parathyroid hormone (PTH) is secreted from parathyroid gland to promote Ca and phosphate absorption by osteocytic membrane from bone fluid. If plasma Ca levels rise, calcitonin is secreted by the thyroid gland to reduce bone resorption by osteoclasts. It is the tabecular bone that is affected by Ca loss in micrograyity, especially weight bearing bones. The human skeleton contains ~1kg of Ca. Ca loss to weight-bearing bones due to a lack of mechanical loading and bone demineralisation can cause risk of fracture due to the increased brittleness and premature osteoporosis. Bone mineral metabolism is seriously affected during spaceflight in that Ca balance becomes negative throughout the flight. The loss of Ca metabolism can yield increased kidney stone susceptibility due to Ca loss in urine which as well as being incapacitating often requires surgical intervention. Oral inorganic phosphate supplements reduce the negative Ca balance from -

200 to -100mg/day but the loss rate remains significant. The reasons for the Ca loss are not known, but it has been suggested that it may be due to the piezoelectric behaviour of bone tissue under stress. The major health hazards include hypercalcemia, long postflight recovery period, and possible irreversible bone loss - after 5 years, astronauts have lower Ca mineral density than normal but near normal levels are achieved after 9 months.

Immune system impairment can occur at a cellular level under microgravity environments [Cogoli 1981]. Immune response to infectious agents is reduced around 3% as much activity as normal - the number of invasive organisms necessary to trigger the immune response system is far higher than normal. Infection levels are thus more severe and recovery is much slower. The number of neutrophils (white blood cells that ingest and destroy bacteria as the body's first line of defence) in the blood increases while the number of esinophils decreases. Human T-lymphocyte population and activity which are involved in cell-mediated immunity is also depressed sharply during the first 2-3 months with further drops subsequently. Immune system activation is less than 35% that of terrestrial levels. Generally infection avoidance is the solution adopted. The immune system exhibits a complete recovery in one week.

The circadian rythm of physiological variables which are synchronised by internal oscillators is affected by external cues (which provide synchronisation) due to altered light/dark cycles, eg. at LEO, there is a 60 minute light to 30 minute dark cycle. The pineal hormone melatonin which affects sleep/wake cycles is decreased by exposure to light. Desynchronisation causes social irritability, sensory misperception, decreased performance and efficiency in tasks, ie. fatigue. The trend towards longer flights has introduced the psychological dimension to manned spaceflight and the operational performance of the crew in an isolated, tightly confined environment (human factors). Spaceflight is psychologically stressful due to physical isolation, social deprivation, confinement, exposure to hazard, and general discomfort. Typical symptoms in Antarctic and submarine crews are sleep disturbance (in 70% of people), depression, irritability and headaches, the intensity and frequency relating to the duration of isolation and confinement. Higher than normal levels of conflict in nuclear submarines and polar research stations are well documented. Selecting astronauts with psychological stability and a high degree of empathy towards others.

The undesirable physiological effects of microgravity on the human body suggest the possibility of using artificial gravity through rotating the spacecraft to generate centrifugal forces in the rotating environment, though radiation and psychological problems would remain [Kramer 1993, Hall 1994, 1999]. Typically, the space station has a spoked wheel design about a central hub for the power plant. Maximum rotation rates have been suggested at 1-3 rpm. Coriolis forces are the major problem with rotationally induced artificial gravity, particularly during motion perpendicular to the axis of rotation. These effects are reduced with increasing radius of rotation.

Acceleration, $a = \ddot{r} + (2w \times v) + w \times (w \times r)$

where $\ddot{r}$ = relative acceleration
r = radial displacement with respect to the centre of rotation
w = angular velocity in inertial space
v = velocity with respect to inertial space

The second term represents the coriolis acceleration and the third term the centrifugal acceleration. Head movements at ~5 rad/s cause cross-coupling between the coriolis and centrifugal forces. It is the coriolis acceleration that produces vestibular illusion of rotation which does not match the visual senses causing motion sickness – the threshold for vestibular illusions is 0.06 rad/s with the onset of nausea at 0.6 rads/s. Hence, space station rotation should not exceed 0.01 rad/s to allow normal head movement in a 1g environment. This would require a radius of rotation of 98 km. Hence, the general dismissal of rotationally induced artificial gravity on space stations.

IMMUNE SYSTEM

Injury to tissue causes inflammation – blood accumulates in the infected area impregnated with leukocytes and fibrinogens (white blood cells). The immune system defends vertebrates against infection. There are ~10^{10} lymphocytes in the human adult blood with ~10^{6} different clones. Antigens are lymphocytes that recognise foreign tissue and are large protein molecules. Each lymphocyte clone shares a unique cell surface receptor that enables them to bind to particular “antigenic determinants” comprising of a portion of a molecule. All lymphocytes develop from pluripotent homopoietic stem cells. They circulate continuously between blood and lymph. The most basic requirement of the immune system is to distinguish between “self” cells and “non-self” foreign cells. The second requirement is to eliminate non-self invaders such as bacteria. In addition, the immune system should recognise and eliminate altered “self” tissue such as cancer. The immune system recognises particular antigens through antibodies and immune cell receptors which bind to active portions of antigens (typically 4-6 amino acids). An antibody is a Y-shaped protein with two identical antigen-binding sites at the tip of the Y and complementary binding sites on its Fc region. If an antibody meets an antigen, the two bind together thereby neutralising the antigen. The strength of antigen-antibody interaction depends on the affinity and number of binding sites. Antibodies de-activate viruses and bacterial toxins and kill and ingest invading microorganisms. Lymphocytes are produced during pre-natal development from stem cells of bone marrow and they have the ability to recognise their own proteins as opposed to foreign bodies. Macrophages are phagocytotic white blood cells which engulf invading microbes and release proteins to activate other parts of the immune system. Cytokines are proteins released by immune cells when activated. They include interferon IL-1 and IL-6 and TNF (tumour necrosis factor). Macrophages produce IL-1 and IL-1 stimulates macrophages to destroy micro-organisms. They comprise the innate/natural immunity system of rapid response. The complementary/acquired immune system works in cascade to identify and destroy invaders. There are two classes of lymphocyte – B cells which make antibodies and T cells which are involved in cell-mediated immunity response. Each B cell clone makes antibody molecules with a unique antigen binding site. Molecules are inserted into the plasma membrane to act as cell surface receptors for the antigen. When the antigen binds to the antibody in the membrane, Be cells are activated to multiply and synthesise quantities of the antibody with the same antigen-binding site which is secreted into the blood. Lymphocytes are specialised white blood cells which multiply when they encounter specific antigen proteins associated with foreign organisms. The body can produce antobodies against a vast variety of potential antigens, ie. the ability is genetically determined (clonal selection). Large numbers of small populations of lymphocyte cells exist, each capable of producing certain types of antibody. Foreign antigens react with particular lymphocyte cell population causing them to amplify the manufacture of that antibody. In the thymus gland, the classes of lymphocytes which would react with the body’s own chemicals are eliminated. Lymphocytes react to antigens by multiplying and transforming into plasma cells. Plasma cells manufacture antibodies from their substantial cytoplasmic and rough ER reserves. The process of mutation and selective proliferation allows the immune system to learn to fabricate antibodies, B cell and T cell receptors which can recognise particular intruders. The immune system can remember the antigen by retaining immune cells with the specific receptors that recognise specific antigens. Antibody or receptor must not bind to self-proteins so early in lymphocyte development, immature B and T immune cells are subjected to a training phase in the thymus where self-recognising receptors are suppressed and eliminated so that the immune system responds only to foreign antigens. The immune system works by clonal selection – most antigens stimulate many different lymphocyte clones. In primary immune response, immune cells with receptors that match a given antigen well are stimulated to reproduce and proliferate by clonal expansion. Strong selection pressure is applied to good recognition immune cells. Lymphocytes are of two types: B lymphocytes secrete defensive antibody proteins that bind to antigens. There are ~100B specific types of B lymphocyte. Each lymphocyte recognises only one antigen and its is DNA mechanisms which provide the diversity. Antibody immunoglobins are large molecules with a characteristic structure – the Ig fold – which serves to recognise non-self molecules. Humans have 5 major types of immunoglobin. All antibodies on a single B cell are of the same type and bind to a specific antigen. If the B cell encounters an antigen, it binds to it and the B cell reproduces to secrete its antibody. Diversity is relieved by genetic processes of both random and inherited components that produce a unique receptor section which is the binding section of the antibody. Each antibody's antigen receptor is formed through interaction between two amino acid chains, one light L and one heavy H. Basic antibody molecule has two pairs of such polypeptide chains and so two antigen receptor sites. Five different classes of antibody (IgA, IgD, IgE, IgG and IgM) each with distinctive H chain (α, δ, ε, γ and μ) which also forms the Fc region to define the biological properties of the class. There are two types of L chain (K or λ but not both) can be associated with any class of H chain. Each immunoglobin L and H chain comprises of variable regions ~110 amino acids residues at its terminal and followed by constant regions. The constant region is the same length in the L chain but 3-4 times longer in the H chain. Each chain consists of repeating and folded domains. The L chain has one variable region V_L and one constant region C_H while the H chain has one variable region V_L and 3-4 constant regions C_H. The amino acid sequence variation in the variable regions are confined to 3 small hypervariable regions which interact together at one end of the molecule to form antigen binding sites. Each anntigen binding site can contact 5-6 sugar residues of the antigen. More than one gene segment codes for each L and H chain. Antibodies are produced from 3 separate gene pools encoding the K, λ and H chains respectively. In each pool, separate gene segments that code for different parts of the variable regions of L and H chains can be brought together by site-specific recombination events during B cell differentiation. Hence, antobody diversity is increased by somatic recombination, by combinatorial joining of light and heavy chains and by somatic mutation. Specificity of the receptor site depends on amino acid sequence of the chain and their arrangements which are specified by gene segments (antibody genes) in the B cell nucleus. There are 3 types of gene segments: V (variable), D (diverse), J (joining). Amino acids of the heavy chain are specified by all 3 segments while the light chain is specified by V and J only. Fourth gene segments C (constant) determines the class of antibody. In humans, V, D J and C segments all lie spaced out on a single chromosome. Segments are located in clusters of 50V, 30D, 6J and 8C elements provide combinatorial receptor diversity. Two gene segments code for V regions of each L chain while 3 gene segments code for V regions of each H chain. To make an antibody, a V gene segment is combined with a J gene segment to produce a V gene for the L chain and a V_H gene is combined with a D and J_H gene segment to produce a V gene for the H chain. Each of the assembled gene products is then co-transcribed with the appropriate C region sequences to produce mRNA molecule that codes for the complete polypeptide chain. By randomly combining inherited gene segments for V_H and V_L regions, vertebrates can make 10^3 different L chains and 10^3 different H chainsthat can combine to form 10^6 different antibodies. Somatic mutation in the gene segments coding for V regions can increase that variability by 10^2. All B cells make IgM antibodies. Some later switch to making antibodies of other classes with the same antigen binding site, allowing the same antigen binding site to be distributed across antibodies with different biological properties. There are other sources of diversity. When joining of V, D and J segments, at the joining boundary between two segments, several base pairs are removed locally and new bases added randomly, thereby changing amino acid sequence and antigen receptor. This allows ~10^6 different variants of antibody molecule from each cluster, each slightly different across two locations (between V and D, and D and J segments). Junction diversity can generate vast diversity of specificity but it is rapid selection of specific antibody by B cells that allows expansion of antibodies. B cells possess immunological memory to reduce delay in combating subsequent infection. T lymphocytes that recognise and kills cells that bear non-self antigen proteins on their surfaces, and enable B lymphocytes to secrete proteins. T cells carry specialised receptor molecules for recognition and it is T cells that inhibit foreign skin grafts. T cell production follows a similar pattern as both T cell receptors and antigens are specified by similar gene mechanisms. Antibodies and T cell receptors are the primary means for immune response to antigens. Killer T cells may encounter infected host cell and kills it. In doing so, the killer T cell hastens the inevitable demise of the cell but prevents a virus from completing the replication process to infect other cells. T cells also help regulate B cell formation. Host defence systems must have arisen at the same time as life itself.

Antibodies recruit the complementary system of K (killer) cells to fight infection. The complement system acts on its own and in cooperation with antibodies in defending vertebrates against infection. Its activation involves sequential proteolytic cascade. It is composed mainly of inactive blood proteins that are sequentially activated in an aplifying series of reactions either by classical pathway which is triggered by IgG or IgM antibodies binding to antigens as complexes, or by alternative pathways triggered directly by cell envelopes of invading micro-organisms. The most important complement component is the C3 protein which can be activated by proteolytic cleavage and then binds covalently to nearby membranes; micro-organisms with activated C3 (C3b) are readily ingested and destroyed by phagocytosis. C3b also initiates assembly of late complement components which form large transmembrane lytic complexes in the membrane to kill cells. Complement activation also releases a variety of small soluble peptides that attract polymorphonuclear leucocytes and stimulate mast cells to secrete histameric – this results in inflammatory response at sites of complement activation. The complement proteolytic cascade is focussed on membranes of target cells by the fact that several of its components including C3b remains activated for less than 0.1s. There are three functionally distinct subclasses of T cells: (i) cytotoxic T cells which directly kill foreign cells; (ii) helper T cells which help B cells make antibody responses, help other T cells make cell-mediated increase responses, and activate macrophages by secreting lymphokines; (iii) suppressor T cells which can inhibit responses of B cells and other cells. Helper and suppressor T cells are the main regulators of immune responses. They interact with their target lymphocytes by recognising either foreign antigens or receptor idiotypes on the target cell surface. Transplantationreactions are T cell mediated immune responses. Most T cells recognise foreign antigens only when these antigens are associated on cell surfaces with membranes glycoproteins encoded by genes in major histocampatibility complex (MHC). In man, they are called HLA antigens. T cells recognise foreign antigens in association with self MHC molecules. There are two main classes of MHC glycoproteins: (i) class 1 MHC glycoproteins are expressed as all nucleated somatic cells and operate by presenting viral antigens to cytotoxic T cells; (ii) class II MHC glycoproteins recognised in association with foreign antigen by helper T cells and which are expressed on most B cells, some T cells and macrophages, and on specialised antigen-presenting cells. MHC glycoproteins serve as primitive antigen-binding receptors to ensure each antigentype involves the appropriate T cell response. These are the most polymorphic vertebrates known as different allelic forms of MHC glycoproteins are ineffective.

The evolution of the immune system is instructive of the evolutionary process. Protozoans are single celled life forms originating ~2.5By ago. Respiration, digestion, defence and many other functions are based on phagocytosis. In all multicellular creatures, phagocytotic cells travel through the circulatory system, coelemic body cavity or tissue spaces. Larva of common starfish typical of invertebrates which appeared ~600My ago utilises phagocytosis as a fundamental mechanism to defend itself against infection. This is the forerunner of the human innate immune system behaviour – invertebrates have thus mastered the ability to recognise self from non-self. Invertebrates make use of precursors of later vertebrate mechanism of immunity. Complement systems also exists in precursor form in invertebrates but without immunological memory or lymphocytes. Ig fold of immunoglobins must have arisen during evolution of metazoan animals as a requirement to recognise and identify self-molecules from differentiated tissue. Perhaps later it became adapted to recognising antibodies in vertebrates. Insects, crabs and worms exhibit prophenoloxidase (proPo) system which is activated by a series of enzymes. Cascade of reactions convert proPo to active enzyme phenoloxidase which encapsulates foreign invaders. There exist antibody-like cells in invertebrates, plants and bacteria – lectin proteins which bind to sugar molecules as cells to make them clumpy. Lectin tag micro-organisms which are covered with different sugar molecules. Lectins are similar to collections in vertebrates which coat microbes to enable easy identification by phagocytes of the innate immune system. Many invertebrates possess molecules related to vertebrate cytokines. These regulate the most primitive immunity mechanisms in vertebrates – different vertebrates have similar IL-1 structures and functions. Worms and tunicates (sea squirt) carry molecules similsr to IL-1 and TNF with similar functions to those molecules in vertebrates. Invertebrates also posses antibacterial proteins such as lysozyme in insects.

Around 500My ago, jawless fish arose with the enzymes of the first immune system based on lymphocytes involving a multi-component adaptive immune system. The first jawed fish appeared shortly later resembling placoderms which had head and pectoral regions encased in protective bony plates including a subclass of elasmobranchs which comprise of cartiligenous sharks, skates and rays ~450 My ago. Sharks and skate both have a spleen which produces B cells and a thymus which produces T cells. They have similar immune systems to mammals. The diversity of their receptors arise from similar mechanisms to mammals though there are some differences. They have 4 different classes of immunoglobins, only one of which is common to humans (IgM). Their antintobody gene segments are organised into clusters. The gene segments V, D and J which specify antibodies are similar to humans with minor differences of organisation. Gene segments are packaged together and often partially joined but these clusters are distributed across many chromosomes. This suggests that mammalian innovation involved duplication of gene segments into multiple Vs, Ds and Js to provide redundancy.

RADIATION SHIELDING

The spacecraft structure must provide a degree of radiation protection to internal components through shielding. Radiation damage to materials are due to displacement and ionisation. The high radiation environment which can cause displacement damage – however this is only a problem at very high fluxes $\geq 10^{18}$ particles/cm^2. Organic materials suffer ionisation while metals tend to suffer from displacement damage. Other non-metals tend to suffer from both phenomena. Energy deposition is measured in rad (radiation absorbed dose)=100 erg/g or Gray=1 J/kg=100 rad (1 rad=6.25×10^7 MeV). A materials ionisation potential is given by $I_{ion}=16.Z^{0.9}$ eV and ionisation causes secondary radiation effects on internal components. Organics suffer major property changes due to radiation exposure especially embrittlement under ultraviolet exposure of 10-30 Mrad. Typically, a 10 Mrad dose will yield 10% hardness, 15% elasticity, 50% elongation, 30% tensile stress and 0.2% mass changes in such materials. Synthetic materials should not be used for external surfaces, eg. teflon degrades significantly if exposed to radiation levels above ~10 krad. Although metals are not significantly affected by radiation doses encountered in space, optical reflective surfaces are affected by low doses ~10^3 rad.

Photons interact with target atoms by producing free electron emissions through the photoelectric effect, Compton scattering and pair production. In photoelectric interaction, the incident photon is absorbed and electrons are emitted mostly from the K-shell. L electrons drop into the K shell emitting X rays. The probability of photoelectric interaction decreases with photon energy and increases with the atomic number Z of the material. Compton scattering with photons of energies exceeding the binding energy of the atomic electrons involves scattering of the atomic Compton electron and a photon of lower energy as the photon donates part of its energy to the electron. Pair production involves a photon with a threshold energy of 1.02MeV striking a high Z target which then absorbs the photon causing electron/positron pair production. Charged particles incident on the target interact mostly through Rutherford scattering which causes excitation and ionisation of atomic electrons. Particle ranges are typically ~10-100μ. Furthermore, energy transferred to atoms can displace them from their normal lattice positions when the imparted energy is sufficiently high ~5-30eV for electronic materials. Subsequently, energy is lost to ionisation with the possible creation of vacancies, defects and interstitials if the energies exceed 2 keV. This can cause changes in energy levels in the bandgap causing in turn the generation and recombination of electron-hole pairs, carrrier trapping and leakage, gain degradation and changes in the carrier concentration and carrier tunnelling. Defects also act as scattering centres reducing carrier mobility. Energies ~MeV can cause defect clusters through knock-on cascading.

Charged particle interactions with the nuclei of materials may generate secondary radiations such as neutron and gamma ray emissions which are more penetrating than the primary incident radiation which increases dose deposition. Heavy ions of high energy >20 MeV penetrate the nucleus coulomb barrier causing proton and neutron ejection within the target material together with gamma ray emission, and possibly even radioisotope creation from alpha-spallation that decays by beta-emission. Energetic proton and neutron fluxes ~1 MeV are ejected as secondary radiations due to nuclear reactions. Above a few 10^3 MeV/nucleon, nuclear reactions exceed atomic ionisation effects. A 400 MeV proton incident on Al will generate nuclear emission of 4.8 nucleons with an average energy of 120 MeV.

Fast electrons in high Z (mass number) materials are slowed by the deceleration of electrons penetrating the material generating the emission of bremstrahlung radiation with a continuous X-ray spectrum. The efficiency of a material is determined by its capability to slow down the incident particle as measured by the linear energy transfer (LET) function. The average X-ray energy is around 30-50% that of the incident electron energy. At energies >10 MeV, bremstrahlung is the dominant energy loss mechanism. The bremstrahlung intensity varies linearly with the atomic number of the material and the square of the electron energy. No reasonable thickness of shielding will significantly attenuate bremstrahlung due to the high penetration of X-rays of due to electron fluxes above 40 keV. Bremstrahlung X-ray doses at any depth is K times less than the electron dose at 1 mm depth where $K=7.5\text{x}10^{-4}$ for Al. Electron dose dominates until Al thickness >8-10 mm at which bremstrahlung becomes dominant. Fast electrons are rare in space.

Low Z materials such as Al, C and B are the most efficient shielding against ions and electrons. Multi-Z shielding with low Z outer material to minimise bremstrahlung radiation and high Z inner shields can provide highly effective radiation protection. Sculptured shields of low Z make optimum use of inherent shielding. The chevron configuration offers physical shielding which allows the transmission of visible radiation but shields against particle radiation [Johnson & Holbrow 1977]. The chevrons are formed from Al right-angled mirrors which form a skin of effective thickness 2l/cos 45. Small spot shields of high Z material such as tantalum of thickness 0.7 g/cm^2 can be used to protect specific components from high energy X-rays. However, SEU is difficult to shield against as are neutrons, necessitating the use of hardened electronic devices. Electron energies <5 MeV (characteristic of the van Allen radiation belts) causes both ionisation and the creation of electron/hole pairs. Proton doses deposit large amounts of energy in materials. In LEO, the total radiation dose is dominated by energetic protons. Above 1000 km, radiation dose increases sharply. A typical space mission will generate an accumulated dose of ~100 krad/20y. The Galileo spacecraft had 0.5cm Al radiation shielding with a radiation limit of 7.5x10^4 rad and 2.5x10^{10}/cm^2 of 1 MeV particle flux. During flares, ~10-20% of the total dose derives from solar protons. A thickness of 0.05 cm Al will stop low energy (~1 MeV) protons but is ineffective against high proton fluxes >30 MeV beyond which proton-induced SEU occurs. Heavy ions of high energy >20 MeV will generate secondary radiation. Such a shield will reduce the average annual dose to ~20 rad (Si)/y for average solar flares but this increases to ~600 rad (Si)/y for anomalously large solar events. Around 0.25 cm of Al shield is optimal against electrons of energy >3 MeV and X-rays up to 3 keV. At high particle fluxes >100 MeV, there is no flux decrease for Al shields ~3.5 cm (10 g/cm^2) thickness, so material shielding is ineffective beyond this thickness. Furthermore, for an Al shield of thickness >3 cm, there is an increase in low energy secondary flux, so the shield thickness must be optimised. Around 10 cm of Al will absorb most heavy ions and this is considered necessary for manned missions.

	Atomic No	Atomic Wt	Penetration depth	Density	Ionisation Potential
C	6	12.01	18.8 mm	2.27	80.25 eV
Al	13	26.98	8.9 mm	2.70	160.94
Pb	82	207.19	0.56 mm	11.35	844.41

Energy attenuation is a function of depth so dosage reduced by shielding is given by:

$E = E_0 e^{-\alpha(t-1)}$ where α=radiation absorption decay constant

t=thickness (in radiation length units)

Mass of shield is given by:

$M = \frac{\rho l A}{\alpha} \ln\left(\frac{E_0}{12\pi r^2 d}\right)$ for a cylindrical shield where A=cross-section

d=maximum radiation dosage

l=radiation length

It appears that an optimal thickness of 3 cm of Al is required to shield the spacecraft from ionising radiations, but this imposes significant mass penalties so is only adopted in manned systems.

SPACE DEBRIS SHIELDING

Debris shielding should be employed. A shield fragments the projectile and spreads its fragments radially to reduce the projectile's original velocity. A typical manned spacecraft has a cross-sectional area of 1500 m^2 with a skin 5mm thick. A Whipple double bumper shield provides an effective debris protection system against fragments ≤1 cm in diameter. The shield breaks up the impacting object so that it strikes the backup sheet over a wider area. The backup sheet may be a pressure wall or kevlar. Perforation damage to the rear wall is minimised provided the spacing between the shield and the rear wall is sufficient [Lambert 1993]. The inclusion of multilayered insulation or honeycomb in the spacing volume can provide even more effective protection. The double bumper shield was used on the Giotto spacecraft which rendezvoused with Halley's comet. Optimally,
t_s/d =0.1-0.2 for an Al-on-Al impact with velocity ~10 km/s

where t_s= bumper shield thickness (in cm),
d=particle diameter (in cm, typically 1 cm)
Thus, t_s=0.2 cm
Backup sheet thickness, t_b=c.M.v/s^2 where c=40
m=particle mass ~10^{-3} g
v=particle velocity ~10 km/s
s=wall spacing (in cm)
=0.4/s^2

Hence, there is a trade-off between satellite size and mass. An 0.1 cm thick Al shield will add ~3 kg/m^2 to the satellite or approximately \$24,000/m^2 in costs. A 2 cm spacing would require a 0.1 cm Al backsheet. Such shields impose mass penalties so a deployable umbrella-like blanket shield in the direction of the orbit may act as a meteoroid bumper (similar to a deployable aerobrake). Debris shields are generally not used in unmanned space platforms and are generally adopted only in manned systems such as ISS or spacecraft that are expected to encounter significant meteoroid fluxes. The ISS has adopted shielding to 1 cm sized debris, but there is a 1-2% per module chance that penetration by a larger piece of debris will occur – with 30 modules, this gives a 24% chance of penetration over 10y and 42% over 20y. However, such a penetration is likely to create a small, slow leak which could be fixed readily by astronauts.