



Machine/Animal Hybrid Controllers for Space Applications Final Report

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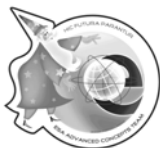
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EXECUTIVE SUMMARY

The aim of the research is to conceptualize a novel insect/machine hybrid controller for autonomous space missions, that hinges around the concept of “insect in a cockpit”; the possibility to include pre-developed insect intelligence capable of sensory-motor integration, decision-making and learning has been investigated.

Nowadays, research activities at the interface between engineering and neurobiology show working devices meant for understanding and reproducing a range of isolated components of complex behaviours. But some tasks, such as navigation towards a distant goal, energy budget maintenance, reaction towards unexpected perturbations, abilities to memorize new experiences and to learn new strategies, require a level of complexity that current control architectures are still far to successfully manage. In this context, the use of insect intelligence could create an intermediate type of mission bridging between purely robotic and human controlled missions.

In order to explore the feasibility of achieving such a challenging goal an interdisciplinary approach has been followed, as hereafter reported.

After a brief introduction (Chapter 1) highlighting background and objectives of the study, in Chapter 2 insect neurophysiology and behavioural patterns have been studied, with the aim of identifying which insect species conjugates navigational capabilities and behaviours that can be easily triggered in space environments.

Then in Chapter 3, the state of the art of insect-inspired robotic platforms has been reviewed; in particular complex tasks requiring multimodal integration and proper weighting of various sensory inputs, e.g. ability to navigate in a complex environment towards a distant goal, have been studied.

The relevant enabling technologies for interfacing the insect with the environment and the robot have been reviewed in Chapter 4, where also current approaches towards hybridity have been presented.

The conceptualized control architecture and its submodules are described in Chapter 5. Both cockpit-based and neural interfacing with the living insect have been considered, particular attention has been dedicated to sensory-motor mapping modules in order to provide to the insect signals as natural as possible. Finally, the main outcomes of the study and possible follow-up plans are outlined in Chapter 6.

1 INTRODUCTION

1.1 *Background and motivation*

Space operations face difficulties when real-time direct control is involved. Both time delay and limited bandwidth narrow the possibility to implement effective real-time remote control of space robots from earth. Hence autonomous behaviour is a key element towards an advanced operational scope during space missions.

Fundamental analogies exist between the behaviours that insects exhibit and basic skills which one would expect from autonomous robots in space. Mobile robots, such as space rovers, should be able to perceive the static and dynamic aspects of an unknown, unstructured environment and modify their behaviour accordingly, very much like real insects do.

Navigation capabilities are the key basic characteristic of mobile robots. Insects such as bees, ants and cockroaches have become particularly appealing models for investigation in the context of biomimetic robotics since they present remarkable navigational capabilities [Whener and Whener, 1990; Whener, 2003; Krapp, 2007; Labhart and Meyer, 2002; Collett and Collett, 2002; Fry and Whener, 2005; Menzel and Giurfa, 2001; Menzel, 2006; Srinivasan, 1996; Jeanson and Deneubourg, 2006; Durier and Rivault, 1999]. They have optimized navigational mechanisms in terms of simplicity and robustness; these features are invaluable characteristics of robotic systems.

Some ongoing research activities at the interface between engineering and neurobiology show working systems meant for understanding and reproducing a range of isolated components of complex behaviours such as flight stabilization, obstacle avoidance, altitude control, directional control and landmark recognition [Abbott, 2007; Diorio and Mavoori, 2003; Franz and Mallott, 2000; Thakoor, 2003; Thakoor, 2004; Paulson, 2004; Franceschini, 2004; Pfeifer, 2007].

What seems natural for an animal is difficult to understand and even more so to reproduce in a robot. For example, foraging animal navigation involves planned, directed locomotion towards a goal (i.e. food source, nest) while negotiating various obstacles and possibly trading off between a successful foraging run (i.e. reaching the desired goal), the time of the run (i.e. the energy budget) and predators (i.e. fatal threats).

The performance difference between a living organism and a conventional robot becomes most apparent in unstructured environments with unknown and potentially hazardous situations occurring in a non-predictable manner. However, unmanned exploratory missions to e.g. Mars or Moon are in general preferred to missions with human presence since these manned missions always present a risk to the astronaut and are extremely costly.

Facing the challenges of autonomous exploration, the range of future automated mission vehicles strongly correlates with the capability of the control architecture to successfully integrate a whole range of decision parameters. In other words, the use of insect intelligence could create an intermediate type of mission bridging between purely robotic and human controlled missions.

In this context we investigate the integration of "animal intelligence" into the control architecture of exploratory vehicles and proper modalities to harvest the full potential of insect intelligence. Our aim is to conceptualize a hybrid controller where insect intelligence acts when decision making and/or cognition are required. In particular we are interested to the integration of tasks such as navigation towards a distant goal, route learning, energy budget maintenance, reaction towards unexpected perturbations, abilities to memorize new experiences and to learn new strategies, which can be classified as high level tasks. These high level tasks require a level of complexity that current control architectures are still far to successfully manage.

1.2 Study objective

The aim of the study is to propose a novel hybrid biological/artificial control architecture, that hinges on the concept "insect in a cockpit". This is definitely a grand challenge, which is better undertaken incrementally, i.e. starting from what is technologically feasible at the present time. For this reason, we critically review the attempts made in this direction.

Given the inherent difficulties, some assumptions have been made in order to facilitate the work:

- i.* Since we want to profit of highly elaborated behaviours observed in living animals, we focus on the use of pre-developed living tissue and do not consider in-vitro development of biological neuronal networks.
- ii.* We assume that it is feasible to keep alive and functional the animal brain tissue (or the whole insect) for a period of time appropriate for space missions.
- iii.* The robotic platform can be designed according to *good practices* taught by biomimetics. In particular we will not take care of control issues which can be solved with a smart (e.g. biomimetic) design.

In order to reach the goal an interdisciplinary approach has been followed *i)* by investigating insects neurophysiology and ethology, with the aim of identifying which behaviours are suitable to be exploited in space environments, *ii)* by critically reviewing current achievements on insect/machine hybrid controllers and *iii)* by investigating technological feasibility of bidirectional interfacing.

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2 INSECT BEHAVIOURS AND NEUROPHYSIOLOGY

The insect capabilities of performing complex tasks despite their miniature brains are an intriguing topic for neurobiology and neuroscience. In the last fifty years considerable research effort has been dedicated to better understand sensory-motor and neural mechanisms related to different behaviours (e.g. navigation, foraging, escape from predators, ecc.).

The results of these studies have been of outstanding interest also for robotics, even if, as specified in the Introduction (Chapter 1), only single components of complex behaviours can be reproduced by machines.

In this context, the possibility to use “living intelligence” to perform high level tasks, such as navigation towards a distant goal, to memorize new experiences and to learn new strategies, could be a great opportunity for developing autonomous machines (i.e. without remote control from earth) in unstructured environments where unknown and potentially hazardous situations occur in a non-predictable manner.

The aim of this chapter is to investigate, by reviewing the state of the art, which insects conjugate both useful navigational capabilities for control purposes and sensory-motor mechanisms that can be easily triggered by natural and/or neural interfaces.

The chapter starts with a review of mechanisms guiding navigation of the most studied insect species (i.e. bees, ants, cockroaches), then insect neural areas mainly involved in high level behaviours are briefly described. Also learning and memory capabilities are outlined and significant models of neural architectures related to the behaviours of interest are presented.

2.1 *Navigation features*

Navigation is the process of planning and following a trajectory from one place to another. It includes choice of direction towards the goal and estimation of the distance to travel to reach it [Gallistel, 1990].

For navigating animals, the most important question is “How do I reach the goal?” rather than “Where I am”; therefore navigation does not always require the knowledge of the starting position.

It has been demonstrated that insects use two main navigation processes: path integration (PI) and landmark-based navigation (LN) [Wehner 1996, Wehner, 2003; Collett and Collett, 2002] that are schematized in Figure 2.1a and Figure 2.1b respectively.

PI provides an insect at any moment with a continuous representation of its position in relation to its starting point; the vector is continuously updated by integrating all distances covered and all angles steered, therefore it depends on simultaneous inputs from a neural compass and a neural odometer [Wehner, 2007].

In the short term PI and LN do not interact, but in the long term visual patterns help keep the PI vector calibrated and the learning of visual landmarks is guided by PI. If a conflict arises between the local vector information indicated by a landmark and the global vector established by PI, the direction indicated by the

landmark takes precedence at least briefly, while the insect may return to the PI strategy if response to the local vector (landmark) is unsuccessful in leading to the goal [Collett and Collett, 2000; Collett and Collett, 2002].

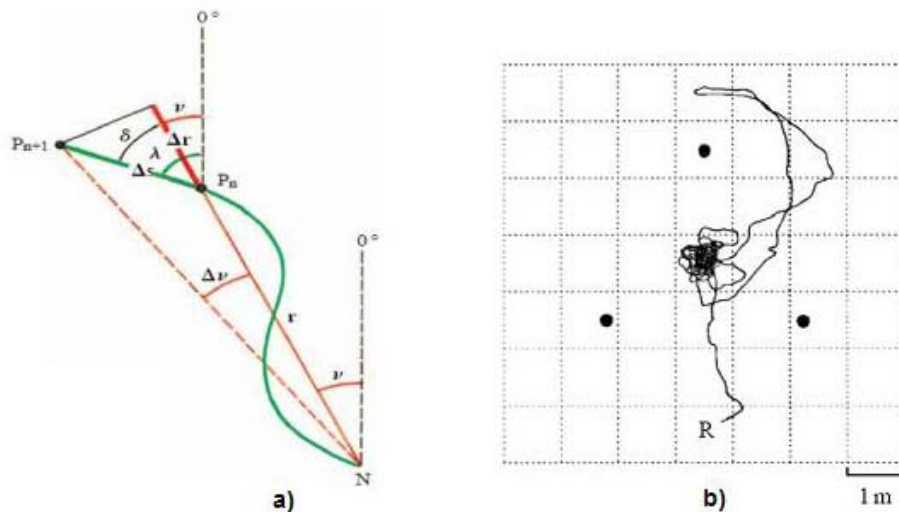


Figure 2.1: a) Path integration scheme; b) landmark based navigation (search pattern of a desert ant, trained to the centre of a triangular array of cylindrical landmarks) [adapted from Wehner, 1996]

Navigational capabilities have been extensively studied in honeybees (e.g. *Apis Mellifera*) [Menzel and Muller, 1996; Labhart and Meyer, 2002; Srinivasan, 1992; Baird, 2005; Lehrer, 2006; Dacke, 2007; Chittka, 2007; Collett and Collett, 2002], ants (e.g. *Cataglyphis*, *Myrmica sabuleti* and *Formica rufa*) [Wehner, 1990; Wehner, 2003; Seidl, 2006; Cammaerts, 2004; Judd and Collett, 1998] and cockroaches (e.g. *Blattella germanica*) [Durier and Rivault, 1999; Jeanson and Deneubourg, 2006; Rivault and Durier, 2004; Ye, 2003].

It has been demonstrated that honeybees and ants gain the compass direction from celestial cues (allothetic cues), in particular from the polarization pattern of the blue sky [Menzel and Muller, 1996; Wehner 2003].

Different methods are used for distance estimation: flying bees measure the distance they travel by recording optic flow [Srinivasan, 1992], while ants are not influenced by self-induced lateral optic flow [Ronacher, 2000] and mainly use “step counting” or proprioceptive information (idiothetic cues) [Seidl, 2006].

It has been demonstrated that desert ants do not acquire a cartographical representation of their foraging terrain, but they use the information provided by their PI and LN systems in a cue dependent procedural way [Wehner, 2007]; on the contrary, honeybees have a “general landscape memory” with the capacity to combine the information from multiple views and movements in a world-centered representation [Menzel, 2000].

Among the different methods for distance and direction estimation, we focused our attention on compass orientation and optic flow recording, because in the “insect-in-a-cockpit scenario” they are suitable to be reproduced by natural interfaces, as described in the Chapter 4.

The compass orientation is used to gauge the travel direction and it is based on the pattern of polarized light in the sky (Rayleigh scattering) but also on spectral

skylight cues, the azimuthal position of the sun, and the direction of the wind; anyhow navigational errors might occur in presence of substantial systematic changes in the sky [Wehner, 2007]. The honeybees are able to learn the measure of sun azimuth from temporary restricted segments, moreover they use landmarks to derive the compass direction under a fully overcast sky [Menzel and Muller 1996].

Sun compassing could be used on Mars, a planet which has no usable magnetic field. Polarization caused by Rayleigh scattering in the Martian atmosphere is detectable in ultraviolet wavelengths; since the degree of polarization is a smooth function of wavelength in the UV range, increasing from 2.2 % at 320 nm to 5 % at 200 nm [Thakoor 2004].

Among the different strategies that insects employ for distance estimation, the optic flow recording is the most interesting to be exploited.

Most insects cannot rely on stereo vision to measure the range of objects at distances greater than a few centimetres. Therefore they need to exploit cues derived from optic flow. The distance flown is gauged by continuously integrating the apparent motion of the visual panorama in the eye [Srinivasan, 1996].

The first experiments that demonstrated how flying insects – and in particular honeybees – use optic flow cues not only to gauge the distances of surfaces but also to discriminate between objects at different distances, to land on a contrasting edge, and to tell an object from a background were performed by Srinivasan [Srinivasan, 1992]. Honeybees flight through a tunnel has been investigated; an apparatus which offered sugar solution at the end of a tunnel formed by two walls, with each wall carrying a pattern consisting of a vertical black-and white grating has been developed. The grating on one of the walls could be moved horizontally at any desired speed; when both gratings were stationary, the bees tended to fly equidistant from the two walls (Figure 2.2a).

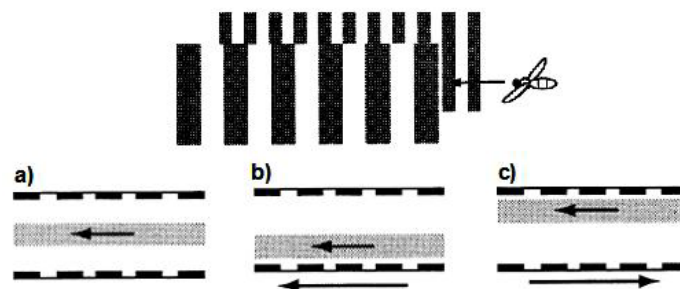


Figure 2.2: Honeybees flight through a tunnel with moving grating walls [adapted from Srinivasan, 1992]

If one of the gratings was moved at a constant speed in the direction of the bees flight, the honeybees tended to fly closer to the moving grating (Figure 2.2b). On the contrary, when the grating was moved in a direction opposite to that of the bees flight, the bees trajectories shifted away from the side of the moving grating (Figure 2.2c). These experiments demonstrate that honeybees balance the retinal images speed on the two eyes.

If the two walls carried gratings of different spatial periods, i.e. different contrast frequencies are experienced by the two eyes, the bee behaviour is the same as the

previous one, thus indicating that the contrast frequencies are not balanced [Srinivasan, 1992].

The “centering” response above described is also used by honeybees to mediate obstacles avoidance [Srinivasan, 2002]. Moreover, it has been proven that honeybees control flight speed by monitoring and regulating angular velocity of the environment image on the eye in order to maintain it constant, i.e. if the tunnel narrows the speed decreases. The mechanism is not influenced by image spatial structure and it is regulated by a visual motion detecting system [Srinivasan, 1996; Baird, 2005].

Honeybees also employ interesting, and probably unique, landing strategy by maintaining constant the angular velocity of the ground on the eye without explicit knowledge of height [Srinivasan, 1996]. Recent analysis of body orientation during flight also suggests that the direction in which the image moves across the eye is very different for flights in the horizontal, oblique and vertical tunnels [Srinivasan, 2007].

Instead of ants and bees, cockroaches have been shown to navigate by using mainly idiothetic cues [Durier and Rivault, 1999; Jeanson and Deneubourg, 2006]. But they also are able to use landmark cues when spatially relevant information is present [Durier and Rivault, 2000]. Besides their navigation capabilities, cockroaches are mainly investigated for their evasive behaviour. The behaviour, accomplished by turning and running, can be elicited by tactile cues, i.e. by antennae touch [Ye, 2003], air displacement (a predator is approaching), that is sensed by wind-receptive hairs on the cerci [Ganihar, 1994] and also by visual cues [Ye, 2003]. This suggests that the escape response is not as simple as once thought and that touch, wind and visual multisensory processing is necessary for obtaining a fully escape response.

Insects capability to generate rich behavioural outputs, by interlinking of path integration, view-dependent ways of recognizing places and landmark routes integration, can be used to perform high level tasks thus having autonomous machines (i.e. without remote control from earth) in unstructured environments where unknown and potentially hazardous situations occur in a non-predictable manner.

In the scenario where we use living tethered insect, species that do not require active walking, that perform distance estimation by optic flow and that use polarized light for gaining direction are to be preferred.

2.2 General features of insect brain

The insect nervous system, mainly consists of a series of ganglia (large aggregates of neurons) linked by thick bundles of axons called connectives; these form the brain in the head and a nerve cord extending through the thorax to the abdomen [Wessnitzer and Webb, 2006].

Reflex-loops form the basis of the insect brain architecture; the interaction of different reflexes, eachone having different gains or priorities, can be achieved by summing the effects of various reflexes (*addition*) or by inhibiting one reflex by another (*switching*), as illustrated by Brooks subsumption architecture [Brooks, 1986].

The insect processing modules are innately specified or tuned to selective and simple forms of learning. The operations of the modules correspond to a vertical processing where single identified neurons or simple neural circuits are involved. However, insect brain provide intelligent solution to a wide range of ecologically relevant problems thus assuring the evolutionary process. Therefore, also the possibility of a central integration that horizontally combines different domain specific modules to form new behaviours and new solutions has been considered [Menzel and Giurfa, 2001]. A possible architecture of insect brain is represented in Figure 2.3.

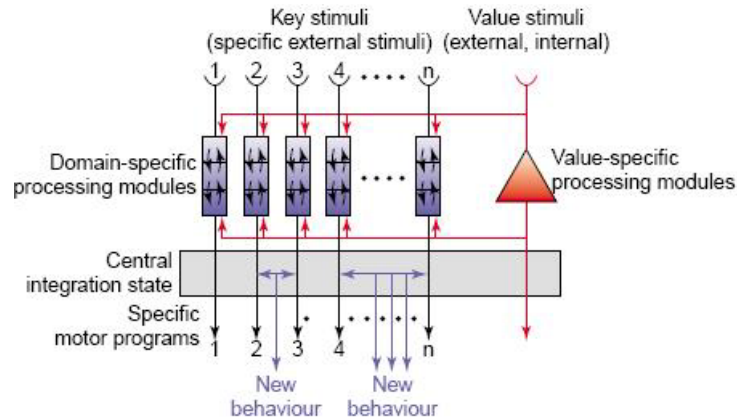


Figure 2.3: Architecture of insect brain [from Menzel and Giurfa, 2001]

Two areas of insect brain have been individuated as association sites of multisensory convergence: the mushroom bodies (MB) and the central complex (CX). The mushroom bodies have major roles in spatio-temporal sensory processing and learning [Menzel, 2001].

The role of the central complex seems to be related with (pre-) motor processing, higher locomotion control, including initiation and modulation of behaviour, goal directed motion and possibly path integration [Vitzthum, 2002; Abbott, 2007]. The central complex has a midline-spanning position (situated between the two brain hemispheres) and a highly regular neuroarchitecture.

Neural levels related to compass direction have been studied in orthopteran insects. Three neural levels have been individuated [Labhart and Meyer, 2002; Krapp, 2007; Whener 2003]:

- i. a group of dorsally directed, highly specialized ommatidia (simple eyes, that form the honeybee compound eye) that serve as polarization sensors (analyzers);
- ii. polarization opponent neurons in the optic lobe that condition the polarization signal by removing unreliable and irrelevant components of the celestial stimulus (integrators);
- iii. neurons in the central complex of the brain that possibly represent the compass output elements, each responding maximally when the animal is oriented in a particular compass direction.

Figure 2.4 reproduced from [Whener, 2003] illustrates the three neuron levels (the number of compass neurons - 24 - has been arbitrarily chosen).

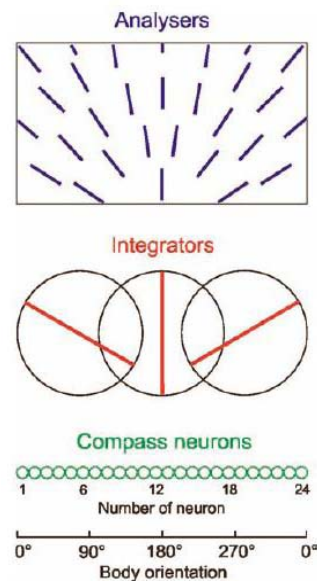


Figure 2.4: Neural levels of insect polarization compass [from Whener, 2003]

One of the most studied nervous structures is the honeybee brain. It is rather small (about $1 \mu\text{l}$ in volume), with about $96 \cdot 10^4$ neurons and it is accessible to recording and manipulation [Menzel, 2001]. A schematic of brain areas is reported in Figure 2.5.

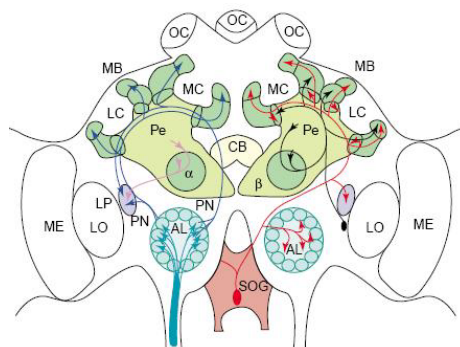


Figure 2.5: Schematic of honeybee brain [from Menzel, 2001]

The *medial calyxes* (MC) and *lateral calyxes* (LC) areas form the *mushroom body* (MB). MB consists of about $17 \cdot 10^4$ tightly packed, parallel and rather similar neurons. MBs receive multisensorial inputs (e.g. mechanosensory, olfactory and visual) and their neurons are able to perform a multimodal computation [Menzel and Giurfa, 2001].

The *antennal lobe* (AL) that is the primary olfactory neuropil, *visual ganglia medulla* (ME), *lobula* (LO), and *suboesophageal ganglion* (SOG), *ocelli* (OC) and the *central body* (CB) are also indicated in the Figure 2.5.

The neural basis of honeybee visual odometer has been investigated by hypothesizing that a non directional, motion-sensitive response could be produced by processing the responses of the large-field, directionally selective motion detecting neurons in the lobula plate of the insect visual pathway [Srinivasan, 2007].

2.3 *Learning and memory*

In the last years several studies have been performed highlighting that insects process and learn information to flexibly adapt to their environment [Menzel, 2001; Menzel, 2006; Cammaerts, 2004; Collett and Collett, 2002; Menzel, 2000; Giurfa, 2001; Mizunami, 1998].

Among the species studied, honeybees have demonstrated to be capable of cognitive performances that were thought to occur only in some vertebrate species [Giurfa, 2001].

Experiments have been performed that suggest how honeybees are trainable to distinguish between objects at various distances [Srinivasan, 1992] as well as they are able to adjust flight patterns according to the information actively acquired; moreover it is the only species that shows a modification of motor patterns based on a learning process [Lehrer, 1996].

Honeybees also have a broad and robust ability to form and use the “sameness-difference” concept, being able to transfer the learned rules to new stimuli, which they had not experienced during training [Giurfa 2001].

A model for the honeybee memory has been proposed by Menzel and Müller. Three different types of memories have been identified [Menzel and Müller, 1996]:

- i)* a transitional short-term memory (STM), susceptible to experiential and experimental interference;
- ii)* a slowly consolidating middle term memory (MTM), which is more stable in the face of new experiences;
- iii)* a long term memory (LTM) formed after training.

The honeybees provide a valuable model for examining neural pathways and their connection to learning, memory and social behaviour [Menzel, 2006]. Moreover, the honeybee genome sequence has been recently completed [<http://www.hgsc.bcm.tmc.edu/projects/honeybee/>] thus providing a great opportunity for better understanding the molecular mechanisms of learning and memory.

2.4 *Neural models*

In the last decade several neural models of insect behaviours have been developed [Hartmann and Wehner, 1995; Chapmann and Webb, 2006; Webb, 2004; Srinivasan, 1992; Menzel, 2001; Wessnitzer and Webb, 2006]. We report the two most significant ones related to ants path integration and bees optic flow exploitation.

The ant path integration has been described at interacting neurons level by Hartmann and Wehner [Hartmann and Wehner, 1995]. The basic idea of this architecture is the concept of activity patterns travelling along neural linear and circular chains, which represent the linear and angular components of movement respectively.

The neural architecture has been modelled as follows [Hartmann and Wehner, 1995]: a chain of neurons with excited (firing) neurons on the left and non-excited neurons on the right is considered. Path length is calculated by summing the path increments Δs over time.

The number of excited neurons counts the number of path increments, the activity edge can be shifted up and down the chain by pulses from neurons s^+ (neuron that fires at a rate proportional to the velocity $\Delta s^+/\Delta t$ and that count positive path increments) and s^- (neuron that fires at a rate proportional to the velocity $\Delta s^-/\Delta t$ and that count negative path increments). Each pulse from neuron s^+ shifts the activity edge by one neuron to the right. Similarly each pulse from neurons s^- shifts the activity edge by one neuron to the left. Representation of cyclical variables by travelling activity peaks also allows simple approximations of goniometric functions as they are used in path integration systems. The systematic error that occurs in real navigation can be reproduced as well.

More recently, evolutionary approach and genetic algorithms have also been used to implement the PI neural model [Vickerstaff and Di Paolo, 2005; Haferlach, 2007].

As regards optic flow exploitation, a model of a non-directional speed detector has been developed by Srinivasan. It allows measuring the local speed of the image independently of structure, contrast or direction of movement. The model consists of four functional stages of processing [Srinivasan, 1992]:

- i) The moving image is converted by an array of neurons in a binary image.
- ii) An array of neurons filters the image, in such a way that a neural moving image with ramps of constant slope results. This process allows monitoring image velocity by measuring the rate of change of response at the ramps.
- iii) An array of physically responding neurons differentiates the neural image by giving a moving image composed of a train of pulses, whose amplitude is proportional to the rate of change of intensity at the corresponding ramp.
- iv) Finally a stage of rectification ensures that the response is positive.

Recently, a general insect brain control architecture for obtaining adaptive behaviour in robots has also been proposed [Wessnitzer and Webb, 2006], as reported in Figure 2.6.

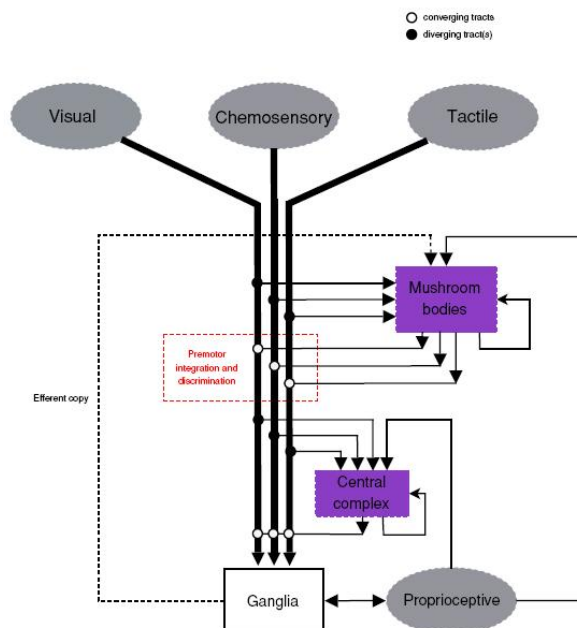


Figure 2.6: Schematic of a general insect brain control architecture [from Wessnitzer and Webb, 2006]

The basis of the architecture are the many parallel domain specific sensory-motor pathways.

Also an indirect secondary pathway is added to the architecture, in order to have an associative memory capable of multimodal sensory integration playing the same role of mushroom bodies.

The central complex inspired the third element of the architecture; it provides solutions to problems of conflict resolution between behavioural modules competing for control of a limited set of effectors.

The final and critical loop of the architecture consists of efference copies of motor commands, that provide predictions of expected sensory events; this information is necessary for distinguishing external disturbances from reafference.

2.5 Conclusions

The topics discussed in this Chapter allow us addressing the problem of selecting the most suitable insect species for our control purposes. All the species described (ants, bees, cockroaches) have prominent navigation capabilities and show complex behaviours. Anyway, the species exhibiting navigation by allothetic cues, with sensory-motor mechanisms that can be easily triggered and that do not require step counting for distance estimation are to be preferred. Also available data on feasibility of both natural and neural interfacing, which will be detailed in Chapter 4, have been taken into account for the insect choice. From the analysis of the discussed topics, honeybee seems to be the most suitable specie.

In order to perform not only a “qualitative” choice but also to summarize the relevant results, we matched all these data in Table 2.1, where a score has been given to each item, according to the reviewed literature.

Table 2.1: Insect capabilities

	Ants	Bees	Cockroaches
“Active walking” not required		XX	
Feasibility of stimulating insect natural sensors (natural interfaces)	X	XXX	XXX
Ability to respond to allothetic (external) cues			
•Celestial	XXX	XXX	
•Visual	XX	XXX	XX
•Olfactive	XX	XXX	XX
•Wind	XX	XX	XXX
Cognitive performances	X	XXX	X
Escape response	XX	XX	XXX
Neural interface technological feasibility	No data	XX	XXX
SCORE	13	24	17

(X=adequate; XX=quite good; XXX=good)

2.6 References

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3 INSECT-INSPIRED ROBOTS

Science fiction movies showed us robots as humanoid machines, difficultly distinguishable from real men.

Real robotics has not achieved the same biomimetic properties of science fiction and probably will never do it, but improvements in that direction are clearly foreseeable. Limitations to this are both from the technological side and from the very conventional thinking that pervades the field of robotics and artificial intelligence. This is often referred to with the acronym GOF AI (Good Old Fashioned Artificial Intelligence), which is criticized to drift every robotic cognition model from the real world domain to that of symbolic, abstract computer algorithms [Harvey, 2004].

A different approach is provided by researchers who are looking at nature to find inspiration for the design of their robots, intrigued by how the various species have adapted to a whole world of environmental niches, introducing the so-called bio-inspired approach in the design of mobile robots.

Biomimetics is a very general term, describing the methodology of engineering a process or a system, which mimics biology [Paulson, 2004]. The term emerged from biochemistry and applies to an infinite range of chemical and mechanical phenomena, from cellular processes to whole-organism functions. Biomimetic robots can be employed for two dual purposes. They can be employed as tools to answer questions about biological processes and as the end products of biological research; they can lead to useful technologies that perform tasks with efficiency and dynamics approaching that of animals [Grasso, 2002]. Especially for what concerns this second class, the degree of detail in which the artificial system should mimic the biological counterpart obviously scales down with the complexity of the artificial system to be replicated.

In this latest case the concept of bio-inspiration is often applied to describe the methodology of engineering a system taking inspiration from biology principles, but without really mimicking the whole biological system. As reported by [Pfeifer, 2007], this approach is justified either by technological feasibility issues (as even a single neuron is too complicated to be synthesized artificially in every detail), or by little interest for a specific application (animals need to satisfy multiple constraints that do not apply to robots), or because the technological solution is superior to the one found in nature (the biological equivalent of the wheel is yet to be discovered).

This chapter will provide a description of the state of the art of robotic platforms whose properties are related to or inspired by an insect equivalent.

Many insect properties have intrigued researchers over the last years, for their appealing properties of obtaining very interesting behaviours with relatively little computational demands, in contrast with what happened for robots. We will describe and classify the state of the art of robotic platforms inspired on insects on the basis of the *main* insect dynamics or behaviour the robot is taking inspiration from, trying to mimic or replicate. The tasks will be classified on high level tasks and low level tasks. This distinction can be considered subtle at times, and one could object that a task which could be solved with a fast response without big computational demands by an insect could appear to be a high level task for a

human. Anyhow we decide to classify locomotion tasks such as walking, climbing, flying or swimming as low level tasks; while behaviours that employ low level tasks, but adding some “cognition”, such as navigation, exploration, foraging, social interaction and decision making are considered to be high level tasks. The following dissertation has no pretence of completeness, but is meant to give an overview into the possible advantages from which robotics can benefit by referring to natural evolution as a useful tool for problem solving.

3.1 Low level tasks implementation

Legged locomotion

Animals such as insects are believed to have one of the most sophisticated locomotory systems in the face of the earth [Ritzmann, 2004]. They process a tremendous amount of sensory information and use it to direct efficient leg and body movements that allow them to move through a range of natural terrains which would be hostile to wheeled vehicles.

Although animal systems can provide exciting inspiration for the design of robotic vehicles, a robot designer cannot simply copy even the simplest animal system into a robotic design, for the earlier described reasons. Thus, the robotics engineer is faced with the question of what animal properties she or he should incorporate into the design. At least one clue in choosing those aspects of animal locomotion to implement in robots is found in the convergent evolution for insects and vertebrates locomotion patterns through complex terrains, as reported by [Ritzmann, 2004]. Where animal groups evolved the same solutions independently, aspects that are similar suggest excellent solutions to physical constraints, providing justification for exporting insect locomotion patterns to structures of different material and/or size.

The design methodology of *functional biomimesis*, embraced by Koditschek and his colleagues [Klavins, 2002], goes in the direction of taking inspiration from *exportable* biological examples, but without being *slavishly yoked* to them. A good solution in deriving practicable engineering design from biological understanding is to develop analogies at the appropriate level of abstraction. In the work by [Klavins, 2002], the authors focused their attention on the *mechanical* end of the animal behavioural spectrum where biology is most constrained by the physical world.

Decades of accumulating evidence from biomechanics suggests that running animals – whether bipeds, quadrupeds or hexapods– perform work on their center of mass so as to exhibit the dynamics of pogo sticks in the sagittal plane [Full and Fearley, 1999]. Their muscles are tuned and postures are selected so as to engage the ground in a compliant manner and bounce from stride to stride.

Together with this general strategy, cockroaches combine an apparent commitment to compliant operation in the horizontal plane, simplifying significantly problems of pitch and yaw stabilization. Recent studies [Kubow and Full, 1999] could quantify the very few degrees of freedom actually used in steady-state running for cockroaches (although complex high-dimensional motions can still be performed by these animals). These running insects produce

leg patterns which take the form of an alternating tripod gait wherein the first and third ipsilateral leg move in phase with the contralateral middle leg; all three antiphase to the opposite tripod. A tripod acts then as a virtual single leg, and the tripod pair is coordinated like as a virtual biped. Hexapods often present a very regular, stereotyped pattern of their steady-state limb motions. A biologically plausible model of how the cockroach generates the alternating tripod running gait is then a CPG (central pattern generator) hypothesis, wherein the legs track a simple feed-forward periodic reference signal. In this view of the animal's coordination control, the pogo-sticks template emerges as an immediate mechanical response, or *prelex*, before any classical feedback response contributes (see Figure 3.1).

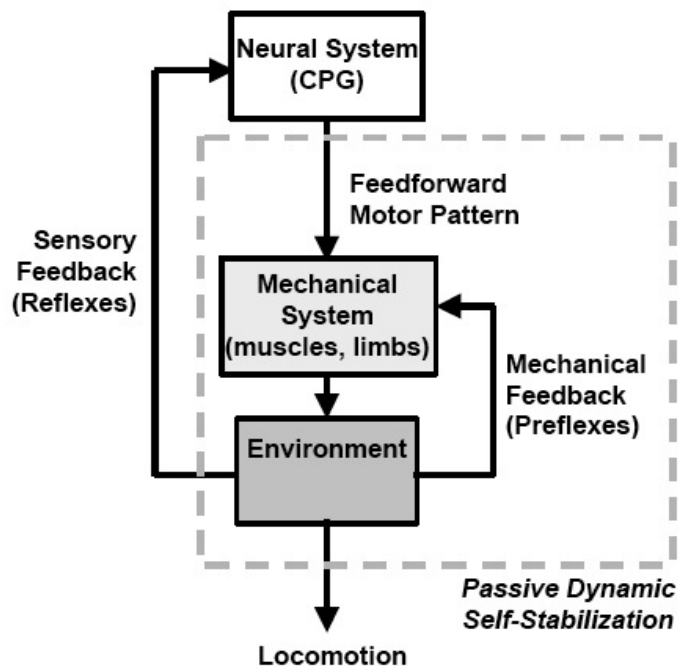


Figure 3.1: Suggested roles of feed forward motor patterns, reflexes and sensory feedback. From [Full and Koditschek, 1999].

These considerations lead to the design and fabrication of a hexapod robot, the RHex, which represents a significant success for functional biomimesis. It weighs 7 kg and has roughly the size (and the appearance) of a shoebox (about 50 cm per 30 cm), and aims at mimicking certain functions exhibited by sprawled-posture runners such as the cockroach species *Blaberus discoidalis*. Its implementation had obviously to deal with technological constraints, such as limited power densities of commercial electromechanical actuators. So RHex borrows from considerations of biological function on this count as well as replacing all but one degree of freedom per leg with a fixed (compliant) shape, locating just one actuator, a 20 W brushless DC servomotor at each of the machine's six "hips". The first hypothesis tested in the robot is the functional biomimesis of the previously described coordination control architecture, implemented in the RHex. In this control architecture leg coordination was imposed simply by sending identical copies of the clock speed reference to the motors belonging to the phase and the anti-phase tripods, with a phase delay of 180°, leaving the function of

adaptation to various terrain irregularities only to the legs (made of Delrin rods), whose viscoelastic properties were designed from simulations of the simple pogo-stick template.

The performance studies [Buehler, 2000] showed how this simple coordination system enabled good adaptation performances in uneven terrains, such as grass and gravel. Authors report that a significant *mechanical intelligence* was exhibited by the variously coupled analogue oscillators that coordinate the intermittent application of ground reaction forces to the robot's body, showing how a bio-inspired design approach enabled to exploit the lowest level of intelligence, which are located in the physicality of the robot.

Similar considerations led to the design of another hexapod robot, the Sprawlita [Clark, 2001].

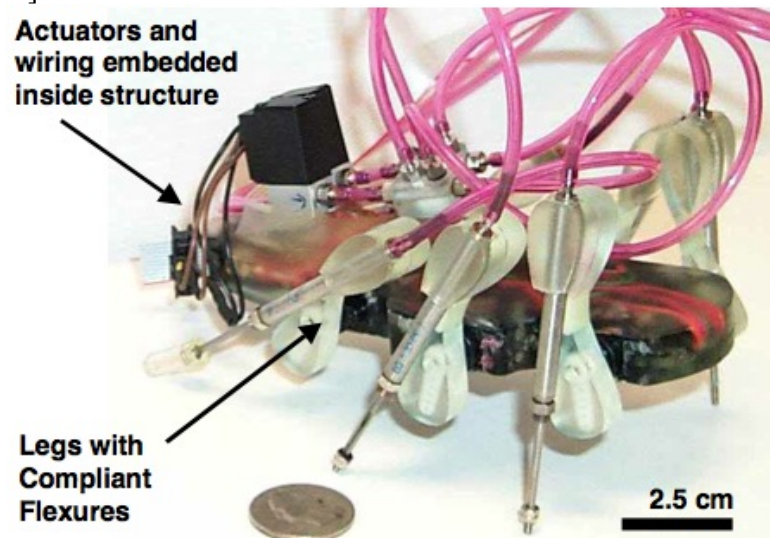


Figure 3.2: A Sprawlita prototype, fabricated with Shape Deposition Manufacturing (SDM) technology. From [Buehler, 2000].

The designers report to have started from the evidence from previous studies underlining the importance of the passive damping of insect legs during locomotion, where are approximately critically damped. The robot was built in order to validate the hypothesis that the combination of a feed forward pattern with a properly tuned and designed mechanical system can lead to the achievement of robust locomotion.

Sprawlita was fabricated by using Shape Deposition Manufacturing (SDM), an emerging layered-manufacturing technology, which enabled to embed the actuators, wiring and connectors into the structure of the robot itself, which could allow to avoid the unreliability of traditional fasteners and connectors. In addition, SDM permits the fabrication of parts with spatially varying material properties, so that the compliance properties of the legs could be varied using a soft grade of polyurethane in specific locations. Each leg consisted of a pneumatic piston attached to a servo through a compliant coupling. This configuration is based on the observation that legs behave as thrusters during locomotion, demonstrated by measurements of cockroach ground reaction forces [Full, 1991]. The feed forward pattern applied to this mechanical system is quite simple. Two three-way valves are activated at a variable stride frequency. Each valve controls air into the three pistons corresponding to one tripod of support. The duty cycle of each tripod,

which corresponds to the percentage of the stride period in which air is supplied to the pistons, determines the relative phase and the amount of overlap between the two tripods. Leg compliance was designed into the hips of Sprawlita, resulting in comparable speeds even without active servo movement, so the leg's swinging motion could be due to the passive compliance at the hip.

Sprawlita could show a robust locomotion also in uneven terrains, with speeds up to 2.5 body lengths per second over obstacles up to hip height (as a comparison, *Blaberus discoidalis* can scramble over obstacles up to three times their body height).

The prototypes presented indicate that without sensory feedback, but with a properly designed mechanical system, legged robots can achieve dynamic performance in rough terrain that begins to compare with that seen in nature.

Aerial locomotion

Insects are the only group of invertebrates to have evolved powered flight. They possess some remarkable flight characteristics and abilities, superior in many ways to anything created by mankind. Some insects, in order to survive in the biological niches where they live, need to be incredibly maneuverable. Typical insect flyers can attain lift forces up to three times their weight and horizontal thrust forces up to five times their weight. There are two substantially different insect flight mechanisms, classified in direct flight and indirect flight; each of these mechanisms has its own advantages and disadvantages, optimized for the given ecological niche where the insect is supposed to live. Insect employing direct flight mechanism (mayflies and odonates) have wing muscles which insert directly at the wing bases, which are hinged so that a small movement of the wing base downward lifts the wing upwards. All other living flying insects use a different mechanism, involving indirect flight muscles; in this case the muscles are attached to the thorax and deform it. Since the wings are extension of the thoracic exoskeleton, the deformation of the thorax causes the wings to move [Dickinson, 1999].

Insect flapping flight provides maneuverability not obtainable with fixed or rotary-wing aircrafts. Moreover, insects can fly with a payload equal to their body mass, with peak accelerations approaching 10 m/s^2 [May, 1991]. These features have intrigued researchers in the field of biologically inspired microrobotics, mostly for the foreseen applications of autonomous high-speed exploration of unknown environments and search-and-rescue. Although they require relatively still air, flying microrobots can fly over terrain that would be impracticable for a legged robot.

Insect flapping-wing flight cannot be explained by steady state aerodynamics and only in recent years there has been elucidation of the unsteady aerodynamic mechanisms, which account for the large lift forces generated [Yan, 2001]. Three key aerodynamic mechanisms used by insects have been identified: *delayed stall*, *wake capture*, and *rotational circulation* [Dickinson, 1999]. In this work wing trajectories that generate lift forces up to four times the equivalent insect weight have been identified, underlining how the wake capture produces significant forces at the top and bottom of the stroke. These results have been used as design input for the design of the micromechanical flying insect (MFI), which targets at

the blowfly *Calliphora* (mass of 100 mg, wing length of 11 mm, wing beat frequency of 150 Hz, actuator power of 8 about mW). In order to exploit the unsteady aerodynamics cited above, each wing must have a flapping range of 140° and rotation range of 90° . Details about the mechanical aspects related to the design (from the kinematic model to the fabrication, including actuation and power constraints) can be found in [Yan, 2001] and [Fearing, 2002], while details about the biomimetic sensorization can be found in [Wu, 2003]. A critical issue is that of delivering a sufficient mechanical power to the wings in order to establish sufficient lift forces (around 0.1 mN for a blowfly). A single-crystal PZN-PT unimorph piezoelectric actuator drives a four-bar slider-crank mechanism, which converts the linear motion of the piezoelectric crystal into an output rotation amplifying it so that, ideally, a 0.1 mm translation is converted into a 180° wing rotation. The required flapping and rotation motions of a single wing was achieved with a wing differential, where two wing spars are driven by two independently actuated four-bars, whose phase lag determines the flapping and rotation angles at each time. The kinematic model was implemented in the reality by polyester micron-thickness flexure joints, suitable to resist to the high level of fatigue stress they are subject (around 10^5 cycles for a 10 min flight at 150 Hz flapping frequency).

For what concerns the sensor apparatus, it serves both for flight stabilization and for navigation purposes. High precision micro sensors were commercially available, but they did not meet the stringent requirements in terms of weight and energy consumption, which concern the MFI. So a biomimetic approach has been used to design these components, such as ocelli, halteres, optic flow and magnetic field sensors.

The ocelli are light-sensitive organs, used to estimate body attitude relative to a fixed frame by comparing the intensity of light measured by the differently oriented photoreceptors. Four IR photodiodes were soldered onto the faces of a square-based pyramid and the voltages across two opposite photodiodes combined differentially in order give a measure of the orientation of the pyramid reference frame relative to the IR light source.

Ocelli can be used to orient insect body towards a specific direction, but its heading remains arbitrary. Since heading is important for forward flight and maneuvering, a magnetic field sensor able to estimate the heading based on the terrestrial geomagnetic field has been proposed.

In flies, halteres resemble small balls at the end of thin rods; they are used to estimate body rotational velocities by sensing gyroscopic forces. As a result of insect motion and haltere kinematics, the force acting on the haltere is composed of many contributions (inertial, gravitational, centrifugal and Coriolis); but the only one of interest for the complete estimation of angular velocity (axis, sign and magnitude) is Coriolis force. This force is detected by two strain gauges, which convert in electric signal the local deformation of a beam close to the point of the rotation caused by the Coriolis force.

Optic flow has been shown to be very important for flight stabilization in flies, since they present an intrinsic response, which generates turn in the direction of the moving visual stimulus in order to reduce the image motion on its eyes [Srinivasan, 2002]. The building block of the proposed motion detection mechanism is an elementary motion detector (EMD) constituted of two

photoreceptors whose perceived signals are compared with a correlation function to the delayed signal of the neighbor, in order to identify the image motion direction. The minimal configuration of two EMDs is used to detect image in both orthogonal directions, thus enabling the optic flow necessary for avoiding obstacles and tracking terrain patterns.

In [Thakoor, 2003] and [Thakoor, 2004] the problematics related to unmanned Mars flying exploration are discussed. The low gravity and nonuniform magnetic field cause increased attitude uncertainty and navigation difficulties and hence an active stabilization employing feedback from high-performance, possibly bioinspired sensors, is crucial. At the same time, exploration of many sites on Mars requires the ability to cover hundreds of kilometers on a very irregular terrain, which makes the mission very suitable to be tackled through an unmanned flyer.

In the same paper insect inspired flight stabilization and navigation algorithms were described and tested in a flyer prototype suitable to be used for space explorations. This prototype has been conceived by capturing some salient properties of a variety of diverse biological organisms adept to flight, applying them to machines that can fly on Mars, as shown by the explicative schematic in Figure 3.3.



Figure 3.3: The concept of incorporating best of class capabilities to develop a hybrid flyer taking inspiration from insects (honeybees and dragonflies) for autonomous navigation algorithms and from mammals (rabbits) for object recognition and tracking. From [Thakoor, 2003].

The flyer is based on a vision system composed of bio-inspired artificial ocelli and sky polarization sensors for regulating heading, which are reported to be a more miniaturizable and lighter solution compared to inertial units used for navigation. Other functions, which require a more intense computation and some kind of cognition, like navigation by reference to recognizable terrain features and hazard avoiding are still difficult to be successfully implemented. On the contrary, natural flying insect can perform well these tasks; despite insect brains contain fewer than 10^{-4} as many neurons as does the human brain. Some of these tasks have been singularly implemented in wheeled robots and are described in the following section.

3.2 High level tasks implementation

Not only basic locomotor or sensory capabilities have been intriguing robotic researchers, but also more complex and abstract tasks requiring multimodal integration and proper weighting of various sensory inputs have been mimicked

by robotic counterparts. The ability to navigate in a complex environment is crucial for both animals and robots. Many animals use a combination of different strategies to return to significant locations in their environment. As an example, the desert ant *Cataglyphis* can explore its desert habitat for hundreds of meters while foraging and return back precisely to its nest on a straight line (see Figure 3.4).

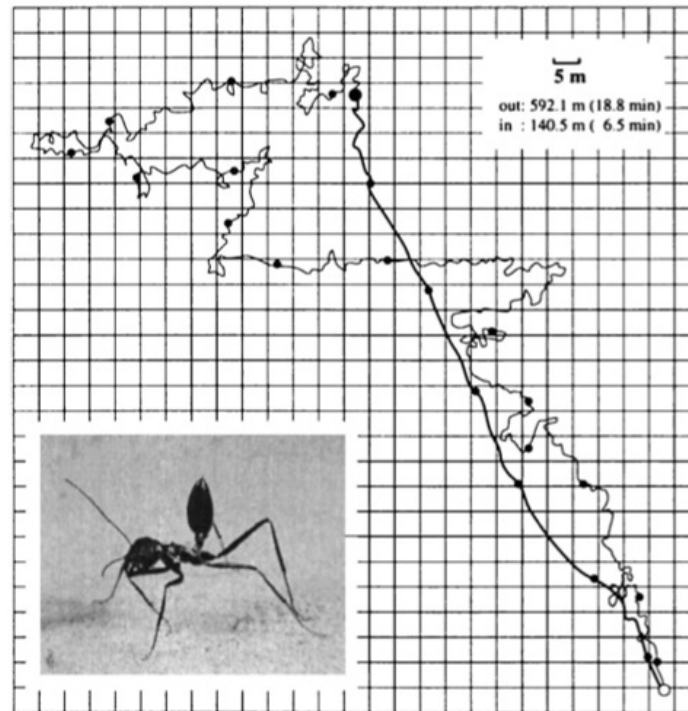


Figure 3.4: Typical foraging trip of the desert ant *Cataglyphis*. The ant starts its trip at the nest (open circle), then it searches for food on a fragmented course (thin line) until it finds a prey (large filled circle). The food is carried back to the nest following an almost straight course (thick line). From [Lambrinos, 2000]

Cataglyphis cannot use pheromones to retrace the correct path and get back to its nest, since the pheromones evaporate in a short time in the high-temperature desert environment. The main strategies that *Cataglyphis* is using to accomplish this task are *path integration*, *visual piloting* and *systematic search*.

In [Lambrinos, 2000], the navigation system of the desert ant *Cataglyphis* has been targeted by researchers of biomimetic robotics and algorithms for path integration and visual piloting were successfully employed on a wheeled mobile robot, *Sahabot 2*.

In “traditional” robotics, distance and directional information useful for path integration are derived from wheel encoders. This method, however, is subject to cumulative odometric errors, which can be reduced by using specialized heading sensors, such as gyroscopes and magnetic compasses. Path integration on the Sojourner Mars rover was obtained with wheel encoders and a turn rate sensor. The errors introduced in the path-integration system were such that the position of the rover had to be updated daily in order to reset the path-integration errors of the odometer by employing a protocol exploiting the observation of the rover from

the lander and the processing of acquired images from Earth. For a distance of 10 m, standard deviations of 125 and 24 cm were predicted for the lateral and the forward errors, respectively. So reaching a target even in a distance of less than 10 m from the lander would require the external update of the position of the rover [Lambrinos, 2000].

Bees and ants employ path integration to return to the relevant locations of their environment, and obtain the compass direction from celestial cues, mainly from the polarization pattern of the sky.

It has been shown that a polarized-light compass implemented in analogue hardware is superior for extracting compass information compared to traditional methods based on proprioception [Lambrinos, 1997]. The POL-compass are based on polarization-opponent units (POL-OP units). They have as a biological counterpart the POL-neurons found in many insects. A POL-OP unit consists of a pair of photodiodes as polarized-light sensors (POL-sensors). In each POL-OP unit the polarizing axis of one POL-sensor was 90° to the polarizing axis of the other sensor. Also this design choice was inspired by crossed-analyzer configuration in the POL-area of insect eyes. Three pairs of POL-sensors were mounted on the mobile robot Sahabot 2.

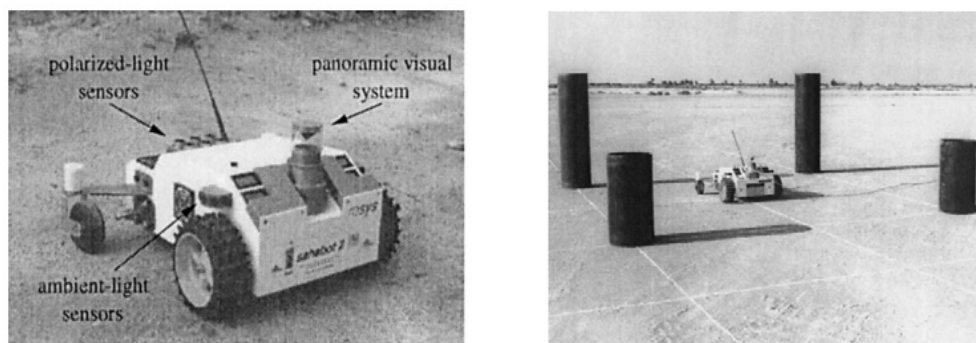


Figure 3.5: The mobile robot Sahabot 2, with its sensory apparatus (left) and in the test environment with cylinders used as landmark anchors and the grid (right). From [Lambrinos, 2000].

A simultaneous model was used for using the POL-OP responses to derive compass direction.

The heading direction is determined continuously and without employing scanning movements during the journey, but an analytical procedure is used to derive compass information from the values of the POL-OP units. This procedure enabled to derive the orientation of the robot with respect to the solar azimuth by using the polarized-light compass, joint with an ephemeris function, which could compensate the effects of the daily changes of the sun azimuth.

The evaluation of the path-integration POL-OP based strategy was performed through experiments performed on a square. Before each experiment, the robot was placed at a defined starting position and aligned with the geographic north. The robot was programmed to follow a trajectory consisting of a number of straight line segments of different orientations and lengths by using one of the two path-integration systems, the POL-compass system or the proprioceptive system. Two indexes were used for evaluating the accuracy of the path-integration POL-compass based method: error of estimation of current position and distance between the final position of the robot and the starting position. The comparative

analysis of results showed that both intermediate position estimation (standard deviation of 67 vs. 29 cm) and final position accuracy (position estimation error of 4.3 vs. 3.3 m) were significantly improved with the POL-compass system.

While path integration employing a skylight compass is the primary strategy that *Cataglyphis* ants use to get in proximity of their nest, the accuracy of the path-integration process is inadequate to estimate the position of the nest, which is invisible to the insect even from a distance of a few meters. For this reason a strategy of *visual piloting* has to be employed in order to finally locate the entrance.

Traditional approaches to visual robot navigation are usually based on determining the robot position from geometrical maps. Typically, the computational complexity required for these methods by far exceeds the limits that can be assumed for insects. Recent changes towards “cheaper” methods replace position-based navigation by methods, which regard homing as the basic navigation ability.

Also in the case of visual piloting for an autonomous robot the exploration of a bio-inspired solution showed to be useful in terms of efficiency and low complexity. To accomplish this task, the desert ant stores a visual snapshot of the scene around the goal position. By matching this snapshot to the current retinal image, the insect can derive the direction where it has to move in order to relocate the target position where the snapshot was taken.

Researchers have tried to mimic this insect behaviour with an image-processing algorithm, which reproduces the matching of home snapshot and current view, reproducing many aspects of the search behaviour of bees. A snapshot is taken at the nest position. When the agent is displaced to a different position, both the azimuthal positions and apparent sizes of the landmark change. A home vector, pointing to the direction of the nest position, can be derived by pairing each sector in the snapshot with the closest sector of the same type in the current view. Each pairing generates two vectors that are attached to the center of the matched sector in the snapshot: a tangential vector pointing towards the paired sector in the current view, and a radial vector, which points centrifugally, if the apparent size of the current view sector is smaller than the size of its counterpart in the snapshot, and vice versa. Both vectors' lengths are proportional to the difference in bearing and apparent size, of the paired sectors.

In order to apply the described algorithm, a camera system was mounted in the front part of the robot, consisting of a digital CCD camera and a conically shaped mirror in the vertical optical axis of the camera, which enables a panoramic, 360° view. When the axis of the cone coincides with the optical axis of the camera, horizontal slices of the environment appear as concentric circles in the image.

Robot experiments have been performed in Tunisian desert, avoiding noon in order to avoid direct sunlight on the POL-sensors. A configuration of two to four cylinders in the plane has been used as landmark configuration, with a grid painted on the desert ground, used to align the landmarks and the robot as well as to record robot trajectories. The robot was placed at the starting position (which symbolizes the nest position and is identical to the target position), and aligned with one of the axes of the grid. At the beginning of each experiment, a snapshot was taken at the starting position, rotated to a standard orientation using the angle obtained from the POL-compass, and stored in the form of black and white

sectors. After taking the snapshot, the robot had to move in a certain direction, symbolizing a short foraging journey of an ant. At the end of this journey the visual homing algorithm assumed the control of the robot, performing the extraction of a sectorized horizontal view from the camera image, then aligning this view with the compass direction. The home vector was computed by matching the aligned view to the snapshot. When the difference between snapshot and current view became lower than a threshold, the target was considered reached.

The precision of the visual homing method has been compared with that of the desert ant. The accuracy achieved in experiments with the robot — final distance to the snapshot location between 7 and 20 cm — is in a range where an ant should be able to see or smell the nest entrance. That was achieved by using a set of only three cylinders as landmark anchors. The computationally parsimonious algorithm allowed the mastering of even complex landmarks, e.g. up to 27 landmarks of different sizes, avoiding the expected result of obtaining local attractor points due to the higher probability of many false matches. The experiments could effectively reproduce the two-phase strategy of orienting for desert ants, consisting in a long-range POL-based path orientation, whose positioning is further refined by a close-range, accurate, vision-based piloting.

A route-learning algorithm has been conceived with a bio-inspired approach and implemented in simulation in [Vardy, 2006]. The robot was manually driven along a required route; at that same time the learning algorithm records snapshot images and associated odometric information from particular points along the route. Initially the robot captures a snapshot image, providing an odometric estimate of the snapshot position. At each step along the route, the robot uses visual homing to compute the angle to the last snapshot position, providing a second estimate of the angle to the last snapshot. The difference between the two angles is mapped to the range $[0, \pi)$; if this difference exceeds a threshold value, a new snapshot is captured. When a new snapshot is captured the previous image is stored as the snapshot image, being added to a list of snapshot images, and an odometry motion vector is also stored, pointing from the previous position of the robot to the position of the last snapshot vector. This algorithm learns the reverse route while traveling along the forward route. The capability of obtaining a successful homing is evaluated for every point belonging to a region around every snapshot position. The region around a snapshot position, for which homing towards that specific snapshot position is successful, is known as *catchment* area. The described algorithm assures that a proper individuation of the threshold angle of odometric difference leads to a complete overlap of catchment areas between adjacent snapshot points.

In the same work, a route following algorithm has been implemented with a two-stage process. In the first stage, the robot travels along the current odometry motion vector. It simply turns in the direction of this vector and travels by a distance given by the vector's magnitude. In the second stage, visual homing is used to guide the agent to the goal. Visual homing thus acts to correct for errors in the odometry motion vector, and for further errors that may be caused by moving along this vector.

After each step of visual homing the agent tries to determine if it is sufficiently close to the target. If so, the next stored snapshot is selected as goal and the two-

stage process begins again. A proper tuning of the parameters of the arrival detection routine was used to avoid oscillation around each snapshot position. The implemented algorithms were tested using a software simulation. The route following algorithm was tested, showing how homing tasks were performed without odometry errors. The effect of the variation of the threshold angle has been evaluated, showing that its increase lowers the number of screenshot positions acquired. Globally, the algorithms presented in the described work showed to perform quite successfully within the unmodified environment.

Other functions of insects, which have widely inspired roboticists for the implementation of bio-mimetic algorithms in autonomous robots, are related to their sociality, which allows gathering abilities and forces from various components of a group of individuals to achieve a common goal.

In order to control the behaviour of a group of robots, collective robotics was often inspired by the collective capabilities of social insects. Aggregation is one of the simplest self-organized behaviours, but also one of the most useful. It allows an individual to transmit information in an efficient way to many other conspecifics at the same time. It thus favors recruitment processes during food source exploitation or territory defense.

Aggregation is a step toward much more complex collective behaviours because it favors interactions and information exchanges among individuals, leading to the emergence of complex and functional self-organized structures.

Complex consequences of aggregation processes were studied with groups of robots. For instance, [Agassounon and Martinoli, 2002] showed that division of labor can emerge in a group of foraging robots when the size of the group grows. In [Garnier, 2005] a new collective behaviour that is based on the self-organized aggregation of robot is presented, which is inspired on a biological model derived from the mechanism of aggregation of larvae of the cockroach *Blattella germanica*. This algorithm was implemented in a group of (10 or 20) micro-robots Alice, to select collectively an aggregation site between two identical or different shelters. Even though the robots used for the implementation have very limited sensory and cognitive abilities (four infra-red sensors for obstacle detection and local communication between robots, with a PIC16LF877 microcontroller, with 8K Flash EEPROM memory), they are still able to perform a collective decision.

A very simple self-enhanced mechanism underlying the aggregation process has been shown to be sufficient to make the group of robots aggregate around one of two identical shelters, instead of equally splitting between them. If the two shelters are different, the robots preferentially choose the bigger of the two, without being individually able to measure the size of each shelter. The self-enhanced aggregation process associated with a preference can lead a group of robots to a collective choice for an aggregation site. This choice comes from an emerging collective ability to “sense” and “compare ” the sizes of the aggregation site.

Individual robots are unable to perform such behaviours because of their very limited perception apparatus and computing power, and also because of the simplicity of their individual behaviours. This simplicity is not a limit to the appearance of complex collective behaviour. Division of labor, object ordering and even collective decisions can emerge from the numerous interactions between

artificial agents with some very simple behavioural rules. Such associations are challenges to take up if the collective robotics solution, based on self-organized mechanisms and/or biologically inspired behaviours, is chosen as an efficient and robust way to perform complex tasks with groups of numerous small autonomous robotic agents.

The social aspect of living into groups of insects has been explored with a biomimetic approach also in the work of [Halloy, 2007]. In this work the aspect of collective decision-making was taken into account in a mixed group of real and robotic cockroaches (InsBot).

The InsBot biomimetic cockroach robot was developed, in order to obtain a successful integration of the robotic agent with the real cockroaches. The InsBot has similar size (but not shape) of real cockroaches, can move and react to other cockroaches without bumping into insects moving with similar speed avoiding walls and obstacles of different darkness. Sensing occurs through chemical sensors sensitive to cockroaches' pheromones, IR proximity sensors and a linear camera for long range environmental sensing. In insect societies, the interaction between cockroaches is chemotactile and is mainly based on a blend of hydrocarbons coating their body.

Acceptance of robots within a cockroach group is related to the ability of robots to bear the correct chemical signal and to behave appropriately; this feature was obtained through an odor analysis, which enabled natural and artificial agents to be equally attractive to one another.

A circular arena endowed with two shelters is used as experimental environment where to perform tests on the mixed group of cockroaches. In the presence of two identical shelters, each large enough to host the entire group, all the cockroaches choose collectively to rest under one of the shelters. When one shelter is darker than the other, cockroaches select the darker shelter. This preference is then amplified through interindividual interactions. This choice is self-organized and does not require leadership but only influence due to the presence of peer conspecifics. A behavioural model representing the time evolution of the number of robotic and artificial individuals in the shelters and outside was used for a quantitative description of the system and as an overall guidance for the design of the robot.

Two sets of experiments were performed in order to evaluate the properties of mimetism of the developed robots. In the first set the sharing of the collective decision-making for shelter selection in mixed cockroach-robot groups was addressed.

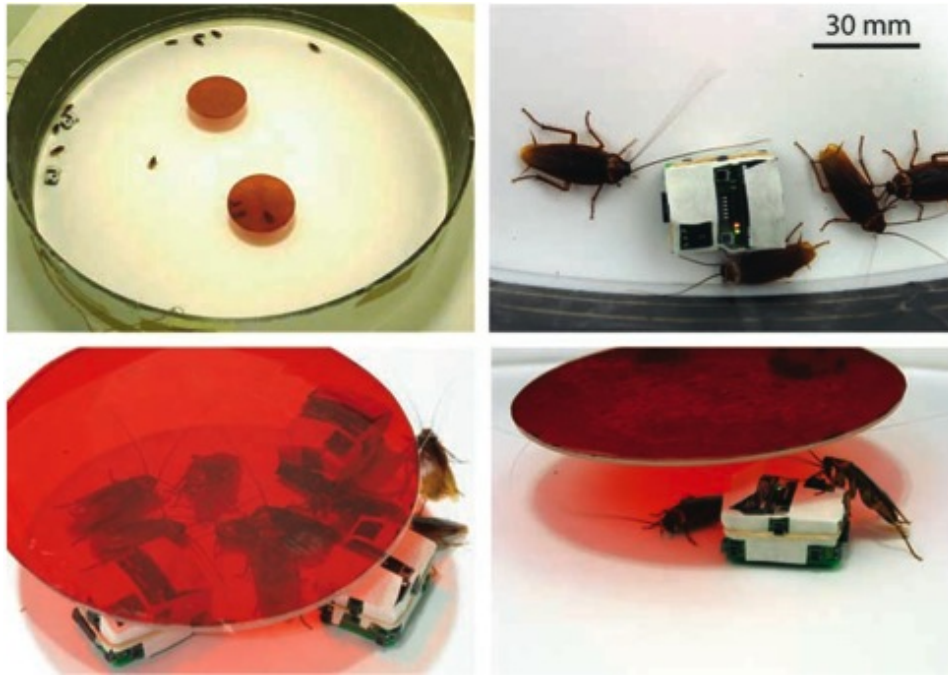


Figure 3.4: The experimental set-up with the robotic and real cockroaches. The shelters are made of plastic disks covered with red films filters suspended above the floor of the circular arena, whose darkness is changed by varying the number of layers of red film. Cockroaches aggregate under the shelter, normally preferring the darker one (from [Halloy 2007]).

The robots were programmed to select dark shelters as cockroaches do. Interactions between robots and cockroaches led to the selection of a common shelter. Given the choice between two identical shelters, both types of groups chose to nest under one of the shelters and behaved as a whole, irrespective of their natural or human-made origin. The second set of the experiments was designed to evaluate the possibility of assigning to the robots the collective choice when shelters differed in darkness. Cockroaches prefer to aggregate under the darker shelter. When cockroach groups selected one of the shelters, the darker shelter was selected in 73% of the cases. In the case of mixed groups, the robots were programmed to prefer the lighter shelter; under these conditions the lighter shelter was preferred in 61% of cases by the mixed group composed by either real and robotic cockroaches, despite the individual preference of real cockroaches towards the darker shelter. The work showed the possibility of shared and controlled collective actions between bio-inspired robots and animals, representing a significant step forward in the field of bio-inspired robotics.

3.3 Conclusions

The chapter provided an overview of some successful attempts in which engineering looked into nature for the design of autonomous robots, following the bio-inspired approach, which has been described. It has been shown how this approach improved the locomotive capabilities of terrestrial or aerial microrobots, which led to lighter structures able to adapt to various environments and suitable to be used as exploratory vehicles for unmanned spatial missions. The capabilities of performing autonomous tasks such as exploration and navigation in unknown environments or collective behaviours have been greatly improved by using insect

inspired sensors and autonomous algorithms. Even though this approach appears promising, the challenge of successfully implementing many concurrent deliberative behaviours still remains open for autonomous vehicles in unmanned space environments. For this purpose also solutions which complement current biologically inspired robots could be pursued.

3.4 References

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4 ANIMAL/MACHINE BIDIRECTIONAL INTERFACES

Machine-insect interfaces can be classified according the following scheme:

- Whole-insect interface (i.e. cockpit interface) (*not-invasive*)
- Interface with part of the insect (*invasive*):
 - o Non-neural interfaces (i.e. stimulating electrode in muscles and EMG recording electrodes)
 - o Neural Interfaces
 - Neural interfacing with cultured neurons
 - Neural interfacing with part of the nervous system of the insect outside the body of the animal
 - Neural interfacing in live animal (Brain Computer Interface-like)

We have to exclude the possibility to resolve high level control issues with interfaces comprised of simple 2D or even 3D neuronal culture. The neurons cultures, e.g. the one described in [Novellino, 2007], are characterized by a random organization in growth that does not correspond to any anatomical substrate for any complex function requiring interaction with the external environment. The contribution of basic neuronal network, such as a neuronal culture could be compared to something like arc-reflex, missing of known computational capabilities.

The higher a given neural system complexity and in a high hierarchy point in ontogenic neural evolution and the more it is able to succeed in high level computational tasks, meaning that we could adapt the original algorithm, proper of the functions played by the area, to our needs with the advantages of maintaining the same inputs and outputs paths of the whole piece. Clear example of this solution was given by the works of Mussa-Ivaldi and co-workers on a small mobile robot double-way linked with a portion of brainstem of a Lamprey in its larval state [Reger, 2000]. They were able to maintain alive the piece in a superfused, oxygenated and refrigerated Ringer's solution for 4-8 hours, the time needed to run the experiment.

Among the possible interfacing solutions, BCI-like interfaces and in particular the feasibility of microelectrodes insertion in the neural ganglia of living insects, will be analysed.

BCIs are tools that decode the neural activity and translate it into specific instructions for a mechanical device or a computer application. To complete this task BCIs do not involve any muscle activity of the user so they are able to satisfy the need of interfacing also in those conditions that involve low or no muscular control and, in general, when no alternative ways of communication are given, thus they can be considered as new output pathway for the brain [Wolpaw, 2007]. A brain to computer interface that is able to transmit information from the nervous system to the machine and viceversa, providing sensory feedback, is defined as bidirectional and it drastically increases the functionality of the controlled system. Many examples of BCI in several different animals, from mice to non human primates are reported in literature [Schwartz, 2004; Lebedev and Nicolelis, 2006; Schwartz, 2006] and even in humans, but few data are available on insects. A complete analysis of the state of the art on BCI in insect will be presented in

Paragraph 4.2, where we critically review implanting experiences, from the simple recording electrodes to fully-embedded bidirectional microsystem.

This is a very promising field to investigate that could succeed in creating the tightness and the right complexity of the relation that we need with the live animal. Unfortunately with this technique problems arise of surgical procedure and all the other typical issues that characterize invasive BCIs in live beings, such as mechanical and electrical stability of the interface along the time of implantation.

An alternative invasive strategy involves, as a different level of interfacing with the live insect, the possibility to create the tight relation *in vivo* with an active muscle. This type of interface could be even bidirectional, e.g. stimulating electrodes to control the muscle contraction or EMG electrodes placed to record its activity, and easier to realize and manage than neural tissue interfacing. On the opposite side the amount and the level of complexity of the information we should be able to exchange will be definitely lower and this could be translated in fewer robot functions that the hybrid controller will be able to handle. Following the same kind of strategy we should analyze also the possibility to interact invasively, with the organs of senses of the insect, reproducing something similar to the way of interaction of the acoustic prosthesis in humans, and if this interfacing technique could evolve in any improvement.

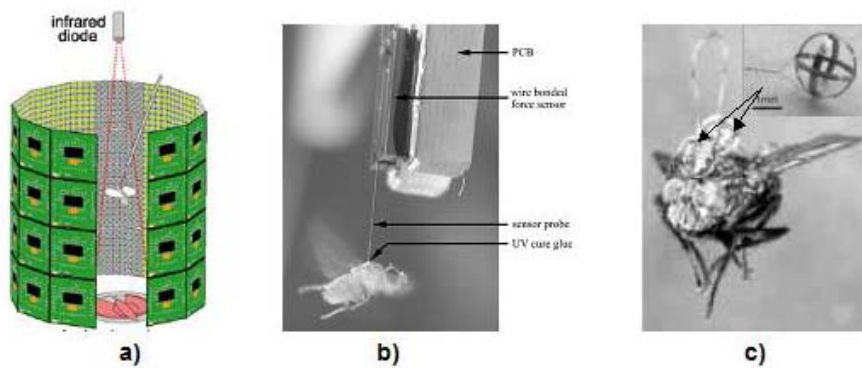
4.1 Natural bi-directional interfaces

Natural interfaces are widely used to investigate insect behaviours triggered by external stimuli through the characterization of insect visual and motor cues.

Several experimental tests have been developed to address behaviours, such as flight trajectory, negotiation of narrow gaps and navigation through obstacles, that can be derived from optic flow recording. Generally, the experimental apparatus for investigating these behaviours consists of a videocamera that records free flying insect in a tunnel. Tunnel walls carried stationary or moving vertical black and white grating and they can have variable width; at the end of the tunnel a reward, e.g. sugar solution, is placed in order to train the insect to perform the required task [Srinivasan, 1992; Srinivasan, 1996; Dacke and Srinivasan, 2007].

The optic flow can be also reproduced to tethered insects by LED panels. In this context, a programmable visual arena (Figure 4.1a), based on panels composed by an 8×8 array of LEDs with individual pixel brightness control has been developed [Reiser and Dickinson, 2008].

Both force sensors and magnetic coils have been used to characterize the insects motor response. Reliable and precise real-time measurements of flight forces in tethered flying fruit flies have been obtained by a MEMS-based force sensor probe glued on the insect [Sun, 2005] (Figure 4.1b) as well as measurements of position and orientation of the thorax have been achieved by sensor coils immersed in a properly generated magnetic field [Schilstra and Van Hateren, 1999] (Figure 4.1c).



Schilstra and Van Hateren, 1999]

An interesting example of natural interfacing between an insect and a robot by decoding motor response through a modified trackball has been developed [<http://www.conceptlab.com/roachbot/>] and it is detailed in Paragraph 4.4 “Current approaches towards hybridity”.

4.2 *In-vivo neuronal bidirectional interfaces in insects.*

The advantages of neural interfaces in insects compared with neural interfaces in more complex animal species are:

- There is a straight one-to-one correspondence between nerve stimulation and muscle activation.
- Insect nervous system can be easily investigated.
- Insect neuron needs low voltage stimulation to excite an axon due to the little insulation [Mavoori, 2004].

The advantages of using a neural interface in insects compared with other kind of interfaces are:

- If the level of complexity of the whole nervous system is too high for our needs we can decerebrate the alive animal, thus improving the strength of the connection between the low neural station and his effectors (i.e. metathoracic ganglia and abdominal muscles in *Manduca Sexta*).
- The amount of current needed to stimulate directly a muscle is about ten fold higher the current needed to stimulate the nerve to obtain the same movement (1mA - 100 μ A) [Mavoori, 2004].

In the past twenty years the efforts of several neuro-ethologists have been spent in investigating the neural basis of locomotion, recording the neural activity in walking insects and correlating it with animal behaviours. At the beginning the very small size of invertebrates results in a hard challenge for engineers trying to evolve new implanted devices thus the most used electrodes were standard suction electrodes. Nowadays the top adopted techniques involve the use of flexible polymer arranged in multi-electrodes array that has the capacity to be bent around a nerve or around an insect appendage enabling multi-unit recording and stimulation, even without affecting the kinematics of the animal locomotion [Spence, 2007].

In 1995 Ye et al., used new kind of electrodes for chronic recordings, similar to cuffs, and implanted them in the nerve cord of a tethered cockroach (*Periplaneta Americana*), close to the thoracic ganglion for a very long time period of about two months. They describe the increase in neural activity linked with spontaneous walking and, after antenna touching stimulation, the presence of large amplitude impulse evoked in the descending interneurons contralateral to the touched antenna and ipsilateral compared to the escape direction. The cockroach turns toward the side of greater activity in descending mechanosensory interneurons away from the touched antenna [Ye, 1995; Ye and Comer, 1996]. The bilateral difference in number of impulse is directly correlated with the angular amplitude of turning; unilateral electrical stimulation through the electrode in cervical connective produces, in absence of touch stimulation, turning movement ipsilateral to the stimulation in the appropriate direction [Burdohan and Comer, 1996; Ye and Comer, 1996].

In this way, it is possible to link one-to-one the activity of single or few neurons with a natural behaviour of the animal and thus it is a concrete algorithm that we could hypothesize to use as a basis for an insect-machine hybrid controller in a similar manner as the Mussa-Ivaldi group did with the Lamprey brain-stem [Reger, 2000]. Both bidirectional neural interfaces, such as electrodes implanted in the cervical area, and other natural interfaces, in input and output directions, proper of the live insect could be considered, as reported in Figure 4.2.

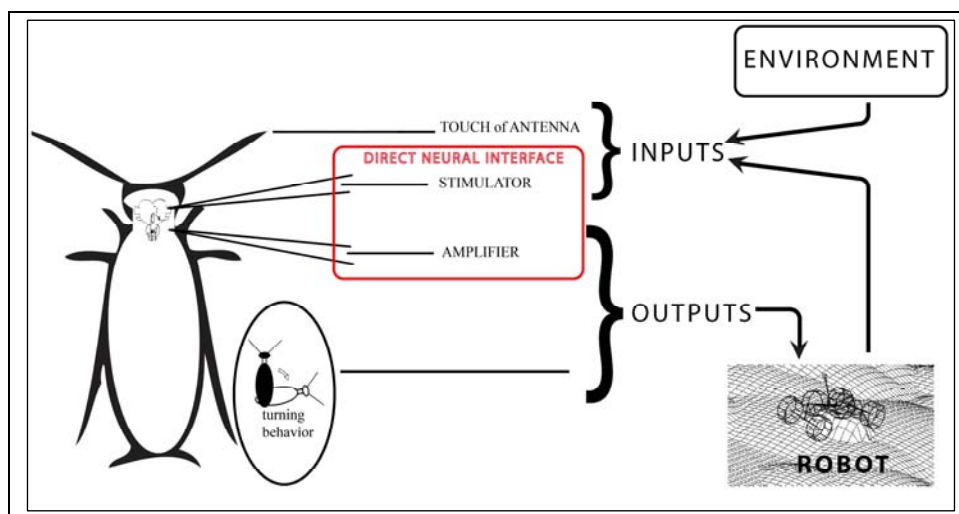


Figure 4.2: Scheme of hypothesized Insect-Machine Hybrid Controller

This hypothesized, but realistic, insect hybrid controller seems to be easy to develop and manage, but it suffers for the simplicity of the neural circuitries taken into account that could allow only low-levels controls. To permit a real “decision making process” we plan to enrich the input and output flows, allowing the exchanging of information through several modalities, both directly interconnected with the neural system of the animal or not. Moreover we want to establish the interface in the way that the insect remains as free as possible and feels itself in a familiar environment (i.e. freely-moving). Final aim is to give to the insect enough information and the right ways to express its higher computational abilities, thus providing to the robot a high level control.

In the same species of insect (*Periplaneta Americana*) Takeuchi and colleagues recently developed a radio telemetric system that allows recording neural activity in freely walking animal in a spatial range of about 16 meters [Takeuchi and Shimoyama, 2004]. The system uses a SMA electrode clipped around the nerve cord along the thorax (see Figure 4.3). It is a concrete step forward in creating an insect-machine neural interface but it was developed only as a recording system, thus, as bidirectional neural interface, it is missing the ability of stimulate the nerve cord.

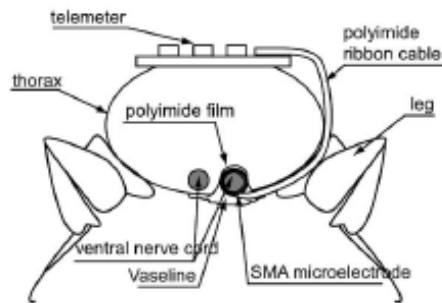


Figure 4.3 - Telemetric System implanted in freely moving *Periplaneta Americana* [from Takeuchi and Shimoyama, 2004]

An interesting microsystem, including on-board memory, able to stimulate and to record from the nervous system of a flying insect light enough to be glued on a *Manduca Sexta* and thus permitting free-fly has also been presented [Mavoori, 2004].

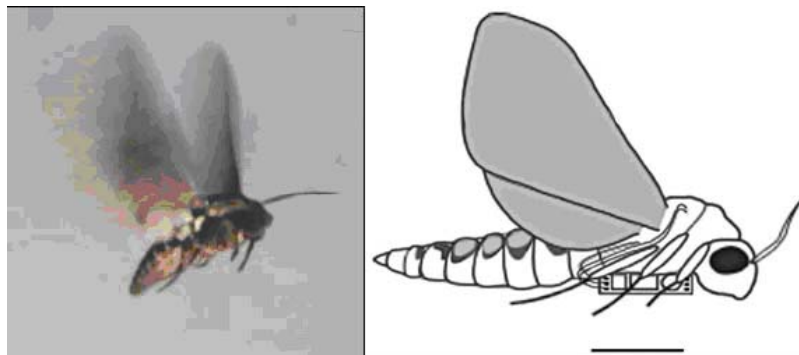


Figure 4.4: Neuronchip implanted in *Manduca Sexta* [from Diorio and Mavoori, 2003]

An example of insect flight control by interfaces implemented in the same bio-hybrid artefact has been recently presented [Sato, 2008]. The system is the ensemble of muscular stimulators, embedded microcontroller and batteries, microfluidic tubes and LED visual stimulator, together with silicon neural probe introduced during the beetle pupal stage. The four neural stimulator are implanted in the flight control area of the brain and close to the wings muscles on either side, while the base of the optic flow device is mounted hanging the LEDs array in front of the head [Sato, 2008].

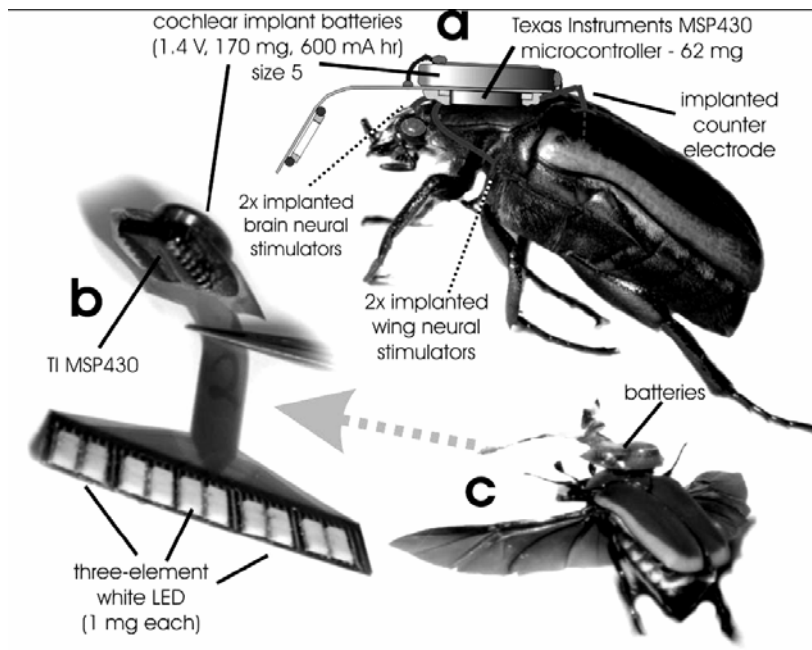


Figure 4.5: Cyborg beetle microsystem [from Sato, 2008]

4.3 Enabling technologies

The first example of an interface for recording insect neural activity has been developed more than 30 years ago by using printed circuit technology [Pickard and Welberry, 1976]. It is based on microfabricated multichannel electrodes able to record unit activity at large numbers of loci simultaneously in relatively free-moving honeybees. The impressive progress of microfabrication technologies lead to develop much more integrated and microsized silicon electrodes. In particular multiple terminals, each $4\ \mu\text{m}$ in diameter, have been fabricated on silicon probes of $30\ \mu\text{m}$ thick, $50\text{--}150\ \mu\text{m}$ wide and $500\ \mu\text{m}$ long, and they have been placed in the path of growing Kenyon cell axons in the pupal honeybee brain [Pickard 1999]. To access neural tissue with minimum damage, extremely fine filaments of silicon, $100\ \mu\text{m}$ long tapering to $3\times 3\ \mu\text{m}$, have been machined to give a “fork-like” primary circuit. Each filament carries a recording terminal of $1\text{--}5\ \mu\text{m}$ in diameter at its tip. Figure 4.6 shows a 4-channel “fork” probe with one recording channel per silicon filament.

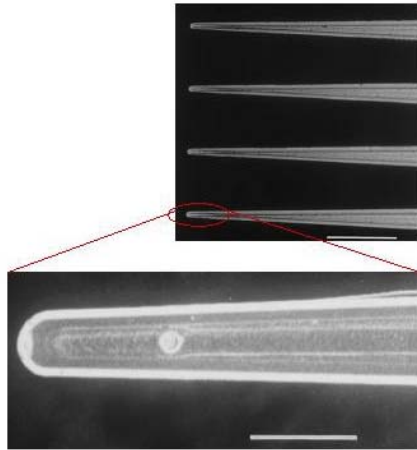


Figure 4.6: Silicon microprobes [adapted from Pickard, 1999]

A microelectrode with a shape memory alloy (SMA) clipping structure has been proposed as a solution to avoid the separation from the nerve caused by animal movement [Takeuchi and Shimoyama, 2000]. The SMA microelectrode makes the operation much easier than the cuff electrodes because it can be actuated by electric heating. This clipping electrode also provides a clear recording signal because of the improved contact between the electrode and nerve.

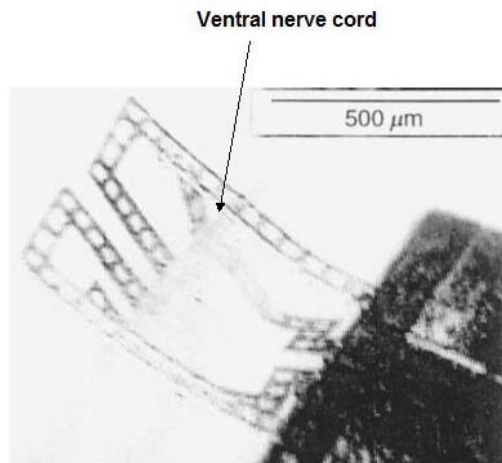


Figure 4.7: SMA electrodes clipped to cockroach ventral nerve cord [adapted from Takeuchi and Shimoyama, 2000]

In order to obtain flexible interconnects between the microelectrode and “outer” electric devices, such as an amplifier or a telemeter, flexible ribbon cables have been designed. The polyimide-based ribbon cable was fabricated by spin coating of polyimide on a Cu foil and patterning by wet etching [Takeuchi and Shimoyama, 2004]. The polyimide offers excellent insulation, flexibility, and biocompatibility. Moreover, the flexible polyimide ribbon cable can be plastically deformed into 3-D shape without fracture.

For these properties, flexible microdevices are increasingly being used for interfacing with biological tissues. Flexible polyimide multielectrodes consisting of a single metallization layer sandwiched between insulating layers of polyimide were developed for recording from multiple neurons or muscles simultaneously in

intact behaving insects [Spence, 2007]. The electrodes have been implanted in cockroaches and both motor and neural activities were observed.

The possibility to dramatically reduce the dimensions of implanted devices thanks to integrated circuit and microfabrication technologies allows obtaining systems successfully implanted in cockroaches, including neural probe, battery and microcontroller whose weight is less than 500 mg [Sato, 2008].

Taking into account that honeybee average weight is about 80 mg and that carried load maximally reaches 80% of body mass [Feuerbacher, 2003], alternative solutions have to be found to implant such devices in honeybees.

4.4 Current approaches towards hybridity

Bidirectional exchange of information between the biological and artificial components of an hybrid controller can be achieved by *i)* natural interfacing (cockpit-based approach), *ii)* neural interfacing and *iii)* combination of both.

To the authors knowledge, the first attempt in the direction of robot control by means of in-vivo intelligence is the Khepera robot controlled by a lamprey brain [Reger, 2000], which we describe although it does not integrate insect tissue. Other examples are the Cockroach Controlled Mobile Robot (Roachbot) [<http://www.conceptlab.com/roachbot/>] and the moth-robot [<http://neuromorph.ece.arizona.edu/>].

Natural interfacing (Cockpit-based approach)

The cockroach-robot has been developed at Irvine University by Hertz [<http://www.conceptlab.com/roachbot/>]. A bidirectional natural interface consisting of eight distance proximity sensors, LED panels and a modified trackball is reported. The robot is used to execute motor commands decoded from movements of an insect positioned on a modified trackball, and to acquire sensorial data about the environment through proximity sensors, encoded into a light stimulus for the cockroach. The system is limited to fleeting behaviour (one of the few behaviours bypassing the central complex), which is simply triggered by stimulus-response very predictable reflexes, thus the hybrid system does not exploit the high-level autonomous behaviours such as navigation and exploration afforded by the insect's brain.

Neural interfacing

One remarkable example of neural interfacing between animal and controller is the lamprey-robot by Mussa Ivaldi and co-workers at University of Chicago [Reger, 2000].

In this case, a neural bidirectional interface is presented. It consists of recording electrodes for acquiring neural data related to the lamprey turning intention, and stimulation electrodes for applying electrical stimuli encoding light intensities recorded by robot sensors.

This ingenious system, however, faces some limitations. First, the purely neural interfacing does not exploit the advantages deriving from the natural capability of the animal to use legs, wings or muscles that can be usefully adopted as input and output signals to/from the system. Moreover, the system can only trigger highly predictable stimulus-response reflexive behaviours.

Natural and neural interfacing

The moth-robot represents the combination of both natural and neural interfacing; it was realized by Higgins and co-workers at Neuromorphic Vision and Robotic Systems Lab, University of Arizona [<http://neuromorph.ece.arizona.edu/>].

In this concept we find bidirectional interfacing consisting of *i*) a natural interface through a continuous optic flow provided by a 14-inch-high revolving wall painted with vertical stripes, and *ii*) a neural interface for measurements of electrical activity of visual motion neurons. In order to realize this approach the moth is immobilized inside a plastic tube mounted on a wheeled robot, which is used only to turn left or right, according to neural signals translated by a computer into action. It is not reported how robot movements influence vertical stripes motion, therefore a closed loop sensing and action behaviour could not be achieved.

Figure 4.8a schematizes the Lamprey-robot: the electrical stimuli are delivered to the axons of the intermediate and posterior octavomotor nuclei (nOMI and nOMP, respectively). Glass microelectrodes record extracellular responses to the stimuli from the posterior rhombencephalic neurons (PRRN). The roachbot and the moth-robot are represented in Figure 4.8b and Figure 4.8c respectively (red circles indicate the insects on the robotic platform).

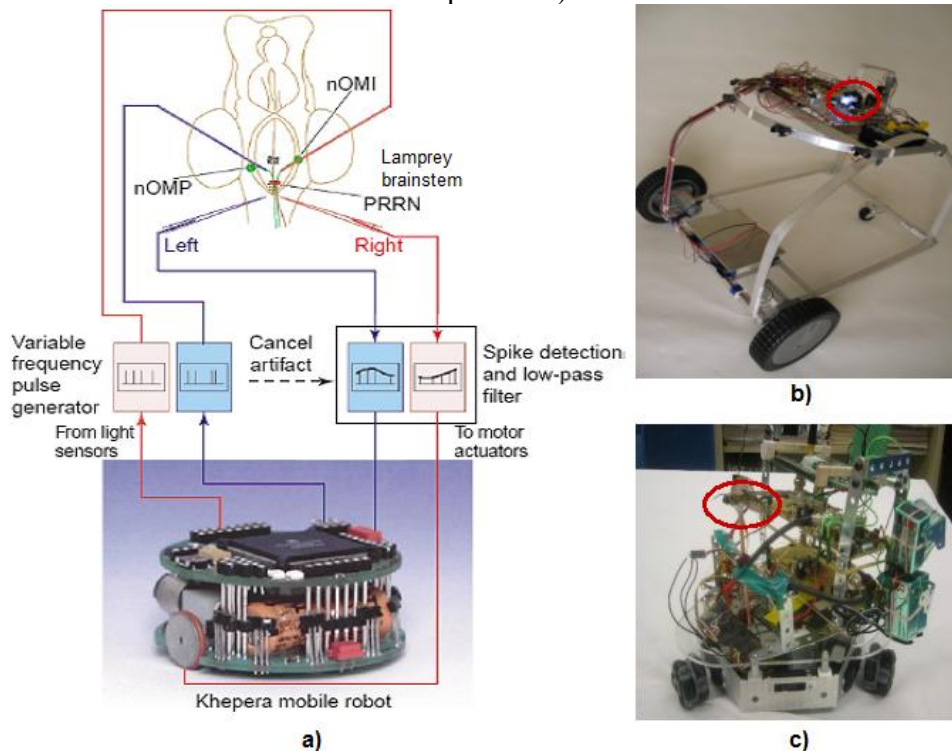


Figure 4.8: Current approach towards hybridity [from a) Reger, 2000; b) <http://www.conceptlab.com/roachbot/>; c) <http://neuromorph.ece.arizona.edu/>]

4.5 Conclusions

Complex issues have to be solved and pros vs. cons have to be carefully evaluated for creating a direct neural interface with the nervous system, especially in our study where two possible needs, i.e. recreate ways of communication, both in

input and output directions, that are no longer useable, and let the normal ways of communication free and available for other uses different from the originals, that justify such complex task are not considered.

Moreover interfacing with the whole insect at a level different from the nervous system allow us taking advantage from the natural capability of the animal to use legs, wings or muscles in general and organs of sense that we can adopt as useful input and output ways to/from the system.

In conclusion, as regard as the neural interfaces, it seems that the more promising way to establish the bidirectional communication needed for the hybrid controller is an invasive direct neural interface “BCI-like” with the live animal that preserve an intact nervous system able of the higher computational tasks. Alternative strategies go toward ameliorating the already developed not-invasive whole-insect interfaces “cockpit-like” or toward improving the interfaces with muscles.

From our analysis the system that can better fulfil the expectations of creating an insect-machine hybrid controller is a system where both neural and natural interfaces work together. In agreement with the present level of the knowledge about neural interfaces in general, and more in particular in insects, it seems not pursuable to consign all the superior control functions of the machine to the insect only connected through a neural interface because of the low grade of robustness achieved today by those devices. Nevertheless the meaning to establish the insect-machine connection at the neural level still persist, taking into account that this way of connection can assure the multimodality of communication and, probably even more important, an increase in the redundancy of information exchanged.

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5 CONCEPTUALIZATION OF A NOVEL INSECT/MACHINE HYBRID CONTROLLER FOR SPACE APPLICATIONS

Success of future automated mission vehicles strongly correlates with the capability of the control architecture to successfully integrate a whole range of decision parameters. The addition of pre-developed insect intelligence in robotic platforms could create an intermediate type of mission bridging between purely robotic and human controlled missions.

In this context we investigated the possibility of integrating "animal intelligence" into the control architecture of exploratory vehicles and proper modalities to harvest the full potential of insect intelligence.

Of course, the choice of an insect and of the surrounding mechatronic systems heavily depends upon the specific task. For this reason, at this point, only very general guidelines can be provided.

From a *methodological perspective*, for a given task of interest the most appropriate insect species can be selected by means of a scoring table, as it was done with Table 2.1 in Chapter 2 having a specific tasks in mind: Mars navigation and exploration.

Once an insect is chosen, we assume we can count on its pre-developed skills to tackle high level tasks, at least when interacting with the natural environment of the insect. Our main interest is to transfer such skills also to different environments (e.g. the Martian soil). No assumption is made that the insect might relearn new skills appropriate to the new environment. Instead, our effort is deploying technology to map outer stimuli from the new environment to stimuli which are natural for the insect.

Although a similar mapping is also required for output motor commands, the sensory mapping is definitely the most challenging part, at least for tasks such as navigation/exploration where motor commands can be only regarded at high level (e.g. move left/right, forward/backward, slow/fast). Effectiveness of such a choice is provided by the cockroach robot [<http://www.conceptlab.com/roachbot/>], where a simple track-ball moved by the cockroach was proved sufficient to steer the robot.

Similarly, once the high level motor commands are available from the insect, these can be used to steer a robot (either wheeled or legged) which should be purposely chosen to deal with locomotion in the new environment. For this reason, for a given task, e.g. locomotion on Martian soil, the most appropriate, state-of-the-art robotic vehicle shall be selected. Such a machine will in general be a complete mechatronic system, with its own modules: sensors, actuators, mechanisms, low level controllers and interface. The latter module shall accept high level commands from the insect.

The next section will describe in detail all the modules composing the proposed hybrid controller.

5.1 The proposed hybrid control architecture

Control architectures for autonomous mobile robots are based on three fundamental paradigms: *i*) Hierarchical Control; *ii*) Reactive Control, *iii*) Hybrid (Deliberative/Reactive) Control [Brooks, 1986; Arkin, 1997; Murphy, 2000; Noreils and Chatila, 1995]. These paradigms differ in the organization of the robot main functions, i.e. sense, plan, act.

In particular the hierarchical paradigm is based on the sequential sense-plan-act model. This organization allows obtaining *a priori* planning of the behaviours and efficient and stable systems. The main limitations are that planning requires search, therefore the response is slow, and that search requires a world model, that can become outdated.

The hierarchical paradigm is schematized in Figure 5.1

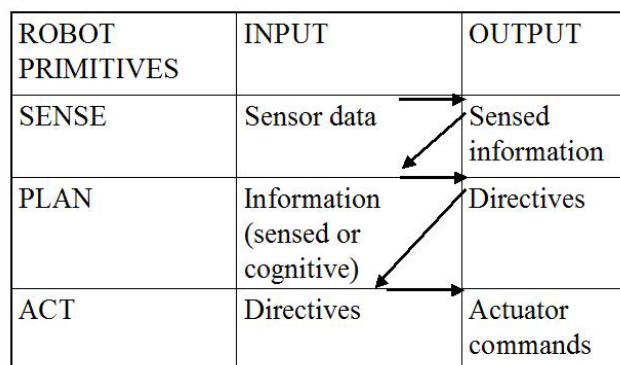


Figure 5.1: Hierarchical control [adapted from Murphy, 2000]

In Figure 5.2 reactive control is schematized. It is a technique for tightly coupling perception (sensing) and action to produce timely robotic response in dynamic and unstructured worlds. It is a powerful method implemented by many animal species, moreover the response to stimulus is very fast, but no memory and learning is considered and it is not possible to plan *a priori* behaviours.

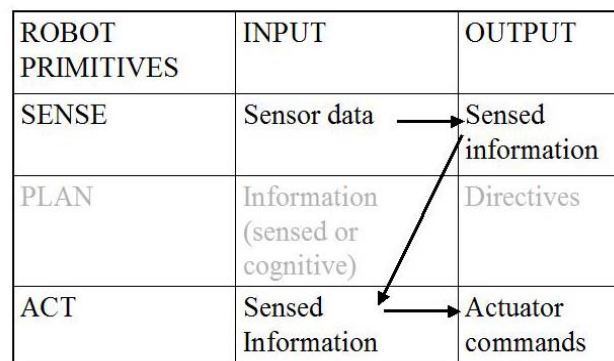


Figure 5.2: Reactive control [adapted from Murphy, 2000]

For our purposes, particular relevance has given to reactive architectures, such as the subsumption architecture proposed by Brooks [Brooks, 1986]. It is predicated on the synergy between sensation and actuation in insects. Brooks argues that instead of building complex agents in simple worlds, the evolutionary path should

be followed by building simple agents in the real, complex and unpredictable world.

The subsumption architecture is built in layers; each layer gives the system a set of pre-wired behaviours. The layers operate asynchronously and the behaviour of the system as a whole is the result of many interacting simple behaviours; each layer implements a recognizable behaviour such as wander or follow a moving object. These layers can be considered hierarchical because higher layers may inhibit the behaviour of lower ones by inhibition or suppression; this gives each level its own "rank of control". The architecture is schematized in Figure 5.3.

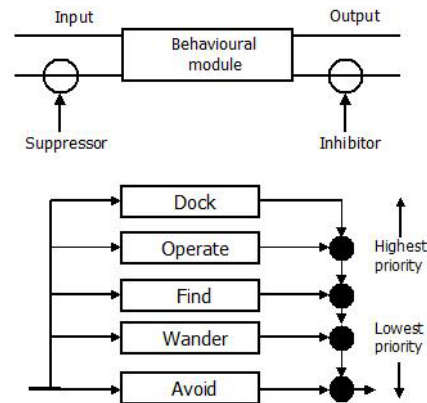


Figure 5.3: Subsumption architecture [adapted from Brooks, 1986]

Finally, the hybrid paradigm combines the deliberative and reactive ones. The hybrid architectures generally have modules for mission planner, sequencer, behavioural manager, cartographer, performance monitoring [Murphy, 2000]. An example of the hybrid paradigm is AuRA - Autonomous Robot Architecture developed by R. Arkin [Arkin, 1997]. The architecture layout is represented in Figure 5.4.

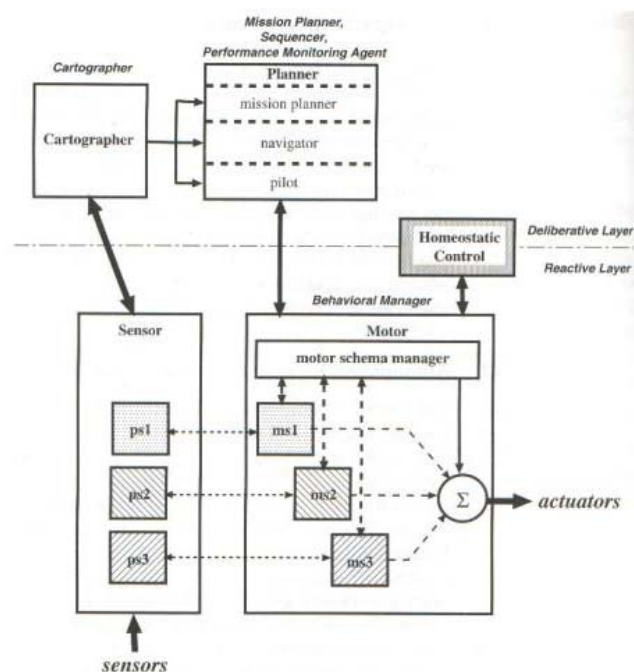


Figure 5.4: AURA architecture [from Murphy, 2000]

In the last five years, starting from the fundamental paradigms described above, several control architectures have been presented for autonomous space exploration vehicles, even if the problems related to management of concurrent behaviours, navigation towards a distant goal, planning and scheduling still remain [Huntsberger, 2003; Thakoor, 2003; Ippolito, 2004; Erikson, 2006; Singh, 2007]. The extensive studies on such aspects of robot navigation as localization and environment mapping led to the definition of a new area of robotics, denoted by the acronym SLAM, which stands for “Simultaneous Localization and Mapping”. An exhaustive overview of SLAM can be found in [Bailey and Durrant-Whyte, 2006; Durrant-Whyte and Bailey, 2006].

These problems can be solved by biological control architectures: recent findings have shown that insects do not merely show reactive behaviours emerging from instincts and reflexes, but also learning and memory processes are implemented in order to adapt to the environment [Menzel, 2006; Menzel, 2000; Giurfa, 2001], as detailed in Chapter 2.

In this context, it has been assumed that insect intelligence can be used for implementing not only reactive but also deliberative behaviours, while from the state of the art it is clearly demonstrated that artificial robotic platforms, e.g. those bio-inspired, are able to better overcome low level issues.

The degree of hybridity of the proposed control architecture has been defined as a trade-off between low-level and high-level behaviours. It is assumed that low level behaviours are managed by the robotic platform, without the direct involvement of the insect intelligence. Since extraterrestrial missions do not usually require fast reactions, several approaches are pursuable in order to have the robot performing the necessary low-level behaviours.

The tasks to be implemented have been restricted to navigation and exploration with compensating reactions towards unexpected perturbations. It has also been considered that the operating environment is very different from the natural environment where an insect may live, therefore inputs from the environment have to be translated into signals, as much natural-like as possible, to be provided to the insect.

According to these assumptions and preliminary considerations, a novel hybrid control architecture has been conceptualized as schematized in Figure 5.5.

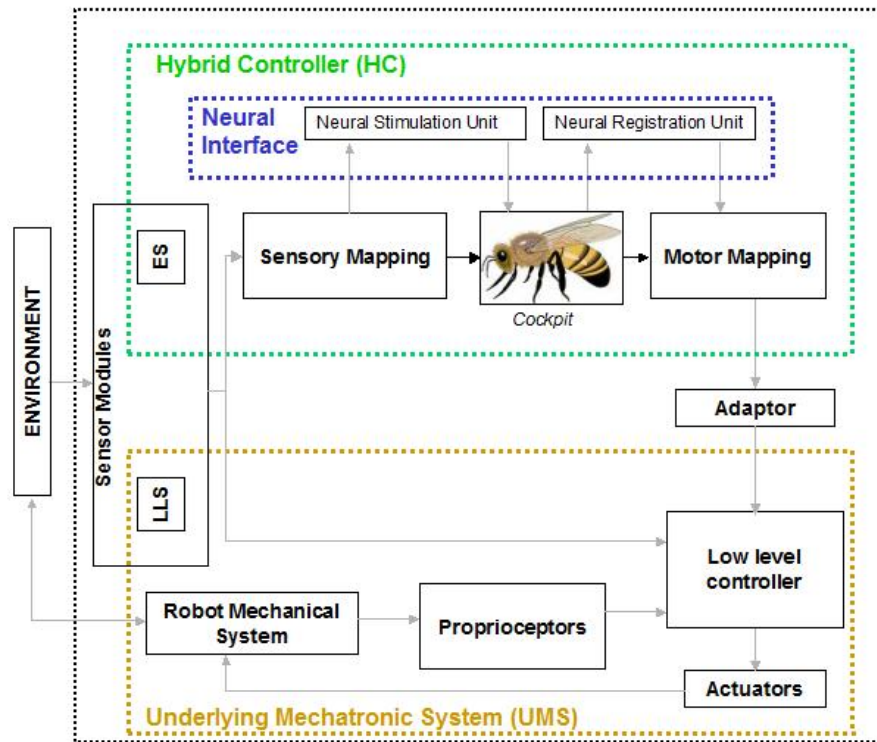


Figure 5.5: Schematization of a robotic platform including the hybrid control architecture

The proposed architecture comprises of three main modules:

- i. the proposed Hybrid Controller (HC)
- ii. the Underlying Mechatronic System (UMS)
- iii. an Adaptor

The general methodological subsequent design steps to be followed for the development of a system based on the proposed architecture are the following:

Step 1: Definition of tasks/behaviours to be featured by the new machine (e.g. navigation and exploration on Mars soil)

Step 2: Insect species choice, according to capabilities scored in Table 2.1 of Chapter 2 and technological issues discussed in Chapter 4.

Step 3: Definition of the *level of hybridity*, i.e. for a given task it should be decided what behaviours (high level behaviours) should be implemented by the insect and what (low level behaviours) should be left to the Underlying Mechatronic System. In case the hybrid controller has to be implemented in a specific given existing robot, the degree of hybridity follows an attentive analysis of its capabilities.

Step 4: Choice of which signals are translated for the neural stimulation and which for the natural stimulation.

Step 5: selection of the Underlying Mechatronic System (UMS). In fact, this decision heavily depends on the available state-of-the-art robotic technologies. For example, when considering navigation and exploration tasks, locomotion

(either wheeled or legged) on rough terrains is reliably achieved by state-of-the-art robots. Proper vehicles have been specifically designed to cope with the nature of the Martian soil, e.g. asperities, presence of sand/dust, local gravity and radiations [Thakoor, 2003; Beard, 2005]. These are ‘details’ which the insect should not get involved with. Note that more than one choice might actually be available.

Step 6: Submodules design. In detail:

Underlying Mechatronic System (UMS)

With reference to Figure 5.5, the relevant mechatronic system sub-modules are:

- **Low-level sensors (LLS)** used to implement low-level behaviours (e.g. locomotion). These sensors are already part of the selected UMS and typically include proximity sensors, inertial modules, wheel\leg encoders and wheel\leg slide sensors for self-stabilization.
- **Proprioception Sensors** used for information related to robot internal state, in particular sensors for energy and failures monitoring.
- **Low level controller** that properly weights inputs from Sensors Module, Proprioceptors and Adaptor (see below), thus allowing the correct driving of the robotic platform.

Hybrid Controller (HC)

The Hybrid Controller basically consists of:

- **Embiotic Sensors (ES)** that complement the original set of sensors of the mechatronic module (LLS). They may include vision systems, temperature sensors, polarization sensors, etc. accordingly to the navigation/exploration tasks. "Embiotic" is a neologism introduced here to distinguish these additional subset of conventional sensors from those required for a proper sensory mapping, which depends on the selected insect. The term comes from Greek prefix "em-" meaning "in, into" and "biotic" meaning "pertaining to life".
- the **Cockpit** where the insect is tethered and able to receive the stimuli both via natural and neural interfaces. For example, the tethered insect receives input stimuli via LED panels and via implanted electrodes, while, the triggered motor response can be monitored by using different type of sensors, e.g. force sensors and electrodes for recording muscle activity.
- **Neural Interface** module, including stimulation and registration units, as described in Chapter 4.
- **Sensory and Motor mapping** modules, that are *the core element* of the proposed architecture and will be described in detail in Paragraph 5.2.

Adaptor

The Adaptor module is designed to process the insect motor commands and to properly give inputs to the low level controller of the robotic platform. In fact, this is the only module that directly joins (at least at a signal level) the Hybrid Controller with the Underlying Mechatronic System. In principle, since multiple choices may be available for the selection of the UMS, a given hybrid controller could easily be adapted to different UMSs by solely changing the Adaptor.

As the proposed architecture broadens its applications in unstructured/dynamic environments, it will have to meet higher standards of robustness, autonomy and cognitive capability. In order to assess the results obtained and to compare them with the state of the art, a benchmark is necessary in terms of adaptability, failure tolerance, robustness and reaction towards external disturbances.

It is a well-known fact that current robotics research makes it difficult not only to compare results of different approaches, but also to assess the quality of individual work.

Robotics benchmarking is a recent active branch of robotics, involving the use of adequate infrastructures [Dillman, 2004]. The National Institutes of Standards and Technology (NIST) underlines that inadequate testing infrastructures result in tens of billions of dollars in additional costs, and significant over-runs in development time [NIST, 2002].

Unifying the infrastructures is pursued in robotics fields where the operating scenario is unstructured, for benchmarking locomotion, mapping, perception and autonomy capabilities [Birk, 2007]. Another approach consists in implementing the different controls under evaluation on the same robotic platform to eliminate variables which depend from the actual hardware in use [Serri, 2004].

Both approaches do not appear to be suitable to benchmark the proposed architecture against other solutions. Indeed, it is quite unlikely that any terrestrial infrastructure can be devised to be fully representative of an extraterrestrial scenario. Secondly, the actual architecture has to be tested when instantiated on the specific robot it is intended to operate with, in order to harness the capabilities offered by the robot specific embodied intelligence. In conclusion, it is necessary to evaluate which are the main features of the control, taking also into account the specificity the environment.

5.2 Sensory and motor mapping

The insect *pre-developed intelligence* is tightly linked to the insect previous experience, to its body (*embodied intelligence*) and to its natural environment; in the framework of this study, abilities of an insect to re-learn to use a different body (e.g. learning to cope with wheeled navigation or use an extra robotic pair of limbs) will be not exploited.

In order to match the pre-developed navigation and exploration skills of the insect with the specific operating environment, a *sensory mapping* mechanism has to be implemented. Navigation and exploration of insects are basically driven by *attractors* and *repellers* elements present in their natural environment. The different typologies of such elements can be simplified in two classes: *static* and *dynamic*.

Examples of basic behaviours that could be implemented during exploration and navigation are reported in Table 5.1.

Table 5.1: Example of exploration/navigation basic behaviours

	attractors	repellers
static	pursuit	avoidance
dynamic	hunting	fleeing

These behaviours are consistently proposed to the insect through the sensory mapping; examples are in Table 5.2.

Table 5.2: Examples of sensory mapping outputs

	attractors	repellers
static	food/home	obstacle
dynamic	prey	predator

All inputs coming from ES sensors are mapped in such a way that they can represent one of the outputs classified in Table 5.2. Simultaneous stimulation of multiple sensory cues will lead to unpredictability of the outcome of the hybrid system due to the complexity of insect decision making mechanisms. Therefore, representation of multi-modal sensorial inputs in an environment able to replicate a situation which is natural for the insect may lead to a true decision making and thus to an autonomous behaviour.

The insect behaviours are triggered by combination and balance of both internal stimuli and external stimuli from the environment. The internal stimuli represent the insect needs and trigger primitive or reactive behaviours, while the external stimuli from the environment can trigger deliberative actions.

For example the primitive needs of the insect, e.g. drink/eat behaviours and the relative temporal cycles, can be used to schedule activities related to energy level of the robotic platform; the path towards the “nest” can be reproduced to the insect by means of optic flow and polarization cues, while decoding of insects torso/head/wing movements by appropriate motor mapping allows driving the robot actuators; when the robot reaches the recharging site, the insect is rewarded with water/food.

Moreover, also landmark navigation and landscape memory can be applied for a complete autonomous navigation without typical drift errors of artificial robotic platform.

The flow of information to and from the insect occurs via a combination of both natural and neural interfaces in order to have redundancy and robustness. The communication established has to assure enough stability and bandwidth to allow correctly driving the robot.

5.3 Conclusions

A doubly hybrid deliberative/reactive and biological/artificial control architecture is proposed by assuming that the underlying mechatronic system of the robotic platform manages low level issues, while directives for performing high level tasks are given by the insect, in this way management of concurrent behaviours

and accurate navigation/exploration without external feedback for drifting errors compensation can be achieved.

A cockpit interface is proposed where the insect is tethered and able to receive the stimuli both via natural and neural interfaces. A close interaction among the interfaces has to be pursued to have redundancy and robustness.

Sensory-motor mapping is conceptualized in order to match the pre-developed navigation and exploration skills of the insect with the operating environment. The adaptor module is proposed to process the insect motor response and to give proper inputs to the low level controller of the robotic platform, thus enhancing the hybrid controller properties in terms of interoperability with different hardware platforms (UMSs).

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6 CONCLUSIONS AND FOLLOW-UP

A novel hybrid controller for integrating insect pre-developed intelligence in a robot has been conceptualized for achieving an unparalleled level of autonomy.

The architecture hinges around the concept of “insect in a cockpit”. The cockpit is a synthetic environment, but perceived as ecological by the insect, that is reproduced inside the robot. Such an environment provides the insect with proper stimuli and records its reactions. The stimuli provided to the insect are consistent with the inputs that the robot receives from the environment, in the sense that the signals perceived by the sensors are biunivocally mapped into sensory inputs that can be processed by the natural insect sensory system (“sensory mapping”).

The reactive/deliberative responses of the insect are interpreted from its movements (“motor mapping”). The motor commands are then translated into inputs for the robot controller by a dedicated module (“adaptor”), which takes into account the actual hardware of the robot.

An additional path has been hypothesized for redundancy and robustness purposes. Such path uses BCI-like neural interfaces directly connected to the insect’s nervous system.

The twofold insect-robot interfacing (i.e. natural and neural) allows the multimodality of communication and redundancy of exchanged information.

The development of the proposed hybrid control architecture can be accomplished through a number of steps, which precede the actual design of each single module. First of all, the performed literature survey has shown that there is not a single best insect for every task. On the contrary, each insect has its own pros and cons. Therefore, the **first step** consists in defining the expected tasks that the robot, by exploiting the insect intelligence, should perform.

The **second step** consists in defining the most suitable insect for the selected tasks. The main criteria for the identification of insect species, which conjugate useful navigational capabilities with easily triggered sensory-motor mechanisms, have been defined using an interdisciplinary approach. In particular, the study of insect neurophysiology and ethology has been merged with the assessment of technological feasibility of bidirectional interfacing.

It appears reasonable to assume that the sensorial burden given to the insect should be kept as low as possible. For this reason, we grouped all the possible behaviours that the robot should exhibit into two classes:

- high level behaviours
- low level behaviours

The first class refers to the behaviours requiring decision making and/or cognitive capabilities (e.g. path planning). The second class includes the remaining behaviours (e.g. obstacle avoidance). We assumed that low level behaviours can be managed by the robot without the active involvement of the insect.

The **third step** consists in defining the *degree of hybridity*, i.e. which behaviours can be considered as “low” and which as “high”. Within this scheme, the “insect intelligence” acts only when decision making is required.

The **fourth step** consists of choosing which signals are translated for the neural stimulation and which for the natural stimulation

The **fifth step** consists of choosing the specific robotic platform.

Finally, the modules comprised in the architecture can be designed in detail.

The proposed concepts represent a first step towards the development of high performance autonomous space exploratory vehicles, but much research effort is still required to develop all the necessary technologies.

As a possible follow-up plan, it should be considered to create a network with other European research groups for the start-up of a project devoted to the development and experimental validation of the conceptualized control architecture. Research groups with expertise in neurobiology, neurophysiology, cybernetics, biomechanics and microengineering should be involved in the project.

The research topics should include the design of sensory/motor mapping and adaptor modules. At first a “cockpit” interface with tethered insects could be implemented. In particular, given the current state of the art, the development of bidirectional neural interfaces appears to be as a medium term goal.

In a second phase an “arena” interface, with freely moving insects (i.e. highly ecological environment), should be considered. In this scenario, the bidirectional neural interface poses additional challenges deriving from the need for autonomy (batteries and telemetry systems should be fixed to the insect).

In parallel, experiments to assess insect capabilities by reproducing space operating conditions should be performed. Eventually, a novel performance\benchmarking metrics should be defined in order to assess the obtained results and to compare them with state-of-the-art autonomous agents performance.