Biomimetics Applied to Space Exploration

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Abstract

A review of the possible applications of biomimetic research and engineering to space exploration is presented. The review begins by briefly introducing biomimicry as an engineering discipline, and then, through considering the characteristics that typify current and future space exploration missions, along with the characteristics commonly associated with biological systems, it is argued that biomimicry has a high degree of applicability to space exploration. Examples of existing, planned and possible uses of biomimetic engineering in application to some specific areas of space exploration are then briefly discussed. A more general discussion then outlines possible future developments that are primarily a consequence of the explosion of knowledge caused by the current genome mapping project, which is increasingly allowing us a much deeper understanding of biological systems at a molecular level. The paper concludes by describing the work being conducted by the Advanced Concepts Team at the European Space Agency into investigating the application of biomimetic engineering to future activity in space.
Keywords: biomimetic, exploration, technology, advanced concepts team, european space agency

1 Introduction

Biomimetics can essentially be defined as the practise of 'reverse engineering' ideas and concepts from nature and implementing them in a field of technology such as engineering, design or computing – for example the development of machines that imitate birds, fish, flying insects or even plants. The ultimate figure of merit of genetic propagation obeyed by all life-forms is obviously not suitable for a human engineered system, which will typically have other goals than reproducing itself. However, in the pursuit of genetic *fitness*, natural systems have found solutions to and optimised (whilst adhering to constraints) numerous subsystems according to the *least energy principle,* which can in addition to genetic *fitness* be considered as an objective function that drives the development of living creatures. A similar situation obtains with engineering, where cost is usually the most significant parameter facing the engineer. Engineering to minimum cost involves, for example, selecting efficient materials, approaching tolerances in structures, and employing efficient manufacturing processes; all tricks used extensively in natural systems. It seems likely then that ideas from nature, suitably interpreted and implemented, could improve the effectiveness, efficiency (and hence reduce the cost) of engineering at many levels.

As a caveat, it should be remembered that whilst biomimicry does indeed have the potential to provide more elegant and superior solutions than more traditional engineering techniques, biomimetic solutions are not always going to be the best choice. Distinctly un-biomimetic engineering artefacts such as the jet or rocket engine have allowed human-engineered systems to perform far beyond biological systems in many ways. Simple observation of the wheel illustrates that nature does not always have the best ideas (although, in fact, rotational motion does exist in one form in the biological realm - the flagellum of bacteria). Biomimetic solutions to an engineering question should not be allowed primacy because they are biomimetic and therefore ‘in vogue’, and practical satisfaction of the broad mission requirements and objectives should be the ultimate objective, not the construction of a biomimetic system because it is pleasing to do so.

2 Application to Space

The initial motivation to include biomimetic engineering as an area of study within the Advanced Concepts Team at the European Space Agency was derived from the opinion that biomimetic engineering could have significant application to future ESA programs. At first consideration, the notion of borrowing from terrestrial lifeforms to provide solutions for engineering a system to operate within a non-terrestrial environment might not seem like a good idea. However, space exploration places unique requirements upon engineering which actually increase the desirability of trying to replicate certain characteristics of biological organisms. In order to understand why this should be so, it is worth considering the typical constraints encountered during a space mission.

Firstly, the environments to be explored are harsh, and to a greater or lesser extent undefined beforehand, with a degree of dynamic variability that cannot be predicted and therefore explicitly accounted for in the design stage of a mission. Consequently the space mission is required to incorporate some measure of reactivity which allows it to compensate and adapt to environmental changes. This is a critical requirement when we consider that on-mission there is usually absolutely no chance of repair, maintenance (the Hubble space telescope is the exception that proves the rule) or resupply, and the spacecraft must be used ‘as is’. This has secondary effects on the requirement for extreme resource and energy efficiency (including an active benefit in being able to utilise resources in-situ). There are typically long communication delays between the ground segment and the spacecraft, mostly due to the enormous distances involved, but also caused by other mission-specific events such as occultations. Incompatibly coupled with these delays is a frequent requirement for intense short-term activity during crucial mission phases, such as atmospheric entry, swingbys and so forth; therefore the spacecraft must be trusted to perform such mission-critical activity without real-time supervision from the ground segment (it is also desirable to reduce the ground segment as much as possible anyway due to the high costs involved). This necessitates, in addition to the reactive capability described earlier, a degree of proactive goal-directed behaviour. Due to the requirement to extract as much utility from a mission (driven by the typically high costs involved) there is also a requirement for highly concurrent activity and therefore effective management between functions.

Characteristics that are common to biological systems include robustness, autonomy, adaptability, intelligence, energy efficiency (including an unparalleled ability to utilise environmental sources of energy) and the ability for self-repair, self-healing and evolution (Emilie et al., [1]). It is immediately apparent that engineering these characteristics into a space mission is highly desirable, given the constraints outlined above. Consequently, there would appear to be good reasons for turning to biomimetic solutions when designing missions to operate in the space environment. For missions to other celestial bodies, given the obvious parallels of planetary environments with the terrestrial environment (solid and liquid surfaces, atmosphere etc.) from which all biological inspiration is derived, it would appear that planetary environments would include additional incentive for copying nature.

3 Application Areas

An initial review of ESA technology development requirements has led to the identification of the following areas to which biomimetic technology is thought to be the most applicable:

- Autonomy and intelligence for spacecraft
- Planetary and orbital robotics
- Control and monitoring of life support systems and crew health
- ISRU (In-Situ Resource Utilisation) implementation.

3.1 On-board autonomy and intelligence for s/c

A general movement towards increasing the on-board autonomy and intelligence of spacecraft can be seen in current missions such as SMART-1 (Elfving et al., [2]) and Deep Space-1 (Muscettola et al., [3]). The drive to increase autonomy has increased due to efforts to improve the survivability and robustness of space missions, and their ability to operate successfully during critical periods for which timely action is required. Increasing robustness will also work to reduce the requirement for the ground segment, typically a primary source of expense for a space mission.

Sources of inspiration for spacecraft autonomy can be taken from a number of classical and biomimetic AI methods. Areas under investigation include reconfigurable neural network control by Yen [4], taking advantage of the ability of neural networks to map and therefore control highly non-linear dynamic systems. This work is directed towards control of large structures such as solar sails or arrays. Both Schetter [5] and Radice [6, 7] have described multiple agent based autonomous systems for satellite constellations. Teams of satellites/space-probes are receiving serious attention now as a means of increasing the capability and reliability (through redundancy) of space missions. Such systems are expected to make use of classical DAI techniques such as scheduling and marketplaces, as well as emergent group behaviours based on simpler 'basis' behaviours - the 'stigmergic' approach described by Bonabeau et al., [8].

Coupled with the drive to increase both the reactive and proactive intelligence of spacecraft is an effort to increase their reliability. The drive towards increasing reliability not only encompasses increasing the durability of hardware, but incorporating an ability into the spacecraft to react to hardware faults through repair or reconfiguration of hardware. This would at best allow completely unaffected performance (or at least 'graceful degradation') in the presence of subsystem failures. Such goals could be accomplished biomimetically by using connectionist control systems (neural networks) that are massively distributed and therefore degrade slowly when subjected to hardware failure of individual components. Neural networks and genetic algorithms have also been proposed for use in health monitoring in a wide range of applications, and this includes monitoring of space systems. For a system that is highly complex with many parameters, neural networks can be used to model the functional relationships between measured parameters where the relationships between parameters are unknown. Work has been done to build failure diagnosis systems for the Space Shuttle main engine using neural networks (Peck et al., [9], Duyar et al., [10]).

Other possible inspiration can be taken from the features that are present in the immune systems found in nature, as well as the mechanisms sustaining the embryonic development of multi-cellular organisms. For example Bradley et al., [11], and Ortega et al., [12] describe a cellular architecture for electronics where every electronic cell in an embryonic array stores not only details of its own configuration, but also those of its neighbours. Such a system would theoretically allow unaffected performance in the presence of one or more individual cell failures (providing sufficient cells remain to provide redundancy).

3.2 Planetary robotics (aerobots, rovers etc.)

Planetary robotics is now seen as an essential enabling technology not only for science and exploration but also for such precursor tasks as scouting and site preparation in preparation for manned missions. Both fully autonomous and partially autonomous biomimetic systems are likely to play key roles in many areas, and there are many possible areas of biomimetic application to space robotics: The use of artificial muscles (e.g. electro-active polymers, shape memory alloys etc.), biomimetic image processing and vision systems, biologically inspired guidance and control for flight and ambulation, drag reduction mechanisms, cooperative guidance algorithms for intelligent swarms, flapping wing flight, smart aerospace structures, and so forth.

Examples of biomimetic control applied to a 'traditional' (i.e. wheeled) planetary rover include the BISMARC (Biologically Inspired System for Map-based Autonomous Rover Control), system, a hybrid neural network/behaviour based control system (Huntsberger et al., [13]), and a mobile autonomous Mars exploration system (Arena et al., [14]). Work into systems that display both form and control biomimicry includes the biomorphic explorers project ('BEES') project (Plice et al., [15]). Another is the entomoptor project led by Michelson [16] that has the goal of a fully autonomous insect-analogue with crawling, swimming and flight capability. The flight system of the entomoptor employs a novel flapping-wing design that actually attempts to avoid the complexities of insect flight to a large degree, through the use of a simple resonant autonomic wing beat with just one degree of freedom. Two wings are set along the fuselage, which then pivot like seesaws with a motion that is 180° out of phase. Because the wings have only one degree of freedom, they cannot employ the tilting mechanism usually used by insects to allow lift generation on the upstroke. Nevertheless, the wings are designed to provide lift on the upstroke through the use of structural materials that react differently to opposing loads. Wing deformation on the upstroke will then yield an angle of attack and camber that produces lift for at least a portion of the upstroke.

At a smaller scale, robotic systems operating at the micro and nano scale have been proposed. The application of MEMs/Nano technology to robotics for space exploration is discussed by Santoli et al., [17], with the goal of merging through solid state microdevices the functions of sensing, computation, communication and actuation. More exotic space applications have been proposed, centered around protein based nano-machines that are constructed from nano-scale elements, such as viral proteins actuators which are based on a conformational change observed in a family of viral envelope proteins (Dubey et al., [18]).

3.3 Control and monitoring of life support systems

Life support systems (LSS) are a crucial technology for the eventual extension of human presence in space. Traditionally life support has been based on physical or chemical processes. LSS technology in development for human support away from low earth orbit (and relatively easy resupply) is focused on increasing the degree of life support loop closure and allowing the production of food. To this end a gradual increase in the amount of biological components (for example bioreactors), that are included into the system will be required. Increasing loop closure necessitates the use of increasingly subtle control systems as the coupling between loops increases. From a biomimetic perspective, increased understanding of ecological mechanisms also has the potential to improve the design and control of life support systems. There is currently little doubt that a holistic ecosystem approach is the most efficient way of constituting life support systems for extended periods of time (Fulget et al., [19]). The tendency of ecosystems to construct, promote and maintain conditions for life, with no explicit control, offers an ideal source of inspiration for the design of life support systems. Another possible source of inspiration is the maintenance of *internal milieu* or homeostasis in organisms, an extremely complex and subtle demonstration of reactive control through a variety of mechanisms (hormonal, neuronal, behavioural) that maintains the state of a living organism. As such, connectionist (neural) control systems, with their ability to map and therefore control highly non-linear systems, as well as adjust through learning, would appear to hold substantial promise in this area.

In tandem with biomimetic control systems such as neural networks, and given the increasingly biological basis of future life support systems, biosensors and biodetectors are likely to play an increasingly important role in LSS control. Biosensors are defined by Gopel et al., [20] as analytical devices incorporating a biological or biologically derived or biomimetic material intimately associated with or integrated within a physicochemical transducer or transducing micro system. One such biosensor project (the German Triple-Lux biosensor project) is scheduled to fly next year.

Life support obviously also extends to periods when the astronaut is engaged in EVA and the life support function is highly localised in the form of a spacesuit. The Chameleon space suit proposed by Hodgson [21] is a biomimetic concept, devised to function like a biological system, using a strategy of adaptive interaction with the environment using multi-functional materials and systems. The objective is to move life support from the backpack and integrate it into the suit at the 'point of need', connecting more closely to the natural processes of the astronaut. The walls of the suit will become complex multi functional structures integrating actuators, sensors, information processing and signal/power transfer. Electroactive polymers are proposed for use in the Chameleon suit to provide thermal control of the suit skin through varying the loft and thermal character of the suit material. The NIAC sponsored astronaut 'bio-suit' system (Pitts et al., [22]) is another example of this approach.

3.4 ISRU systems

ISRU commonly conjurs images of concepts such as propellant production from the Martian atmosphere proposed by Zubrin et al., [23]. However, ISRU extends to the utilisation of any locally available resources, and as such photon collection in space for power generation is another example. Of course, natural systems perform ISRU all the time. The fundamental mechanism for energy capture and synthesis in the natural world is photosynthesis, which occurs in many life forms, ranging from plants to bacteria. The maximum theoretical efficiency of photosynthesis (light energy stored per mole of oxygen evolved) has been estimated to be around 26% and is therefore comparable to existing photovoltaic technology. As a consequence, the use of photosynthesis for a number of applications is currently being considered. The most important application from a space exploration perspective is fuel production. The possibility of using photosynthetic processes to produce hydrogen is beginning to receive increasing attention, and the problem is being approached by exploring the use of existing biological photosynthetic cultures, and through the use of biomimetic mechanisms (AFOSR final report [24]). Photosynthetic mechanisms based on biomimetic technology have also been proposed as a means to enable oxygen recovery in next generation astronaut suits.

3.5 Future directions

Beyond those areas briefly discussed, there are many possible areas where biomimetic technology could have application to space. In particular biomimetic materials technology could be applied across a very wide range of space systems. Materials science is perhaps the most active area of biomimetic research at present, and is rapidly expanding. A huge range of research is being conducted worldwide into areas such as multifunctional block copolymers, self-healing materials, bioadhesives, organic/inorganic hybrid materials and hiearchical structures. These efforts are likely to yield new materials and fabrication methods that find application to all areas of space systems.

Most interestingly, the increasing understanding of the mechanics of cellular function, made possible through modern bioinformatics and the genome revolution, is likely to lead to molecular engineering of particular biological mechanisms to solve engineering problems (Mjolness & Tavormina, [25]). The 'bottom-up' approach to fabrication that nature uses (as opposed to the plant-based methods we currently use), coupled with the information generated from the genome revolution, has the potential to revolutionise the types of, and the way that we construct, materials. This enormous new field of knowledge of course has the potential to revolutionalise space engineering: Biofabrication and morphogenesis in space, because of the requirement for low launch mass, will be a key driver for future large-scale space engineering projects. In all ISRU instances for example, biofabrication techniques, have the potential to render normal plant-based ISRU concepts defunct, allowing the possible molecular and macromolecular scale fabrication of useful resources such as propellants.

The genome and bioinformatics revolution could also have far-reaching consequences in the treatment of the problems associated with space travel on the human physiology. Identification of the function of specific genes, as well as understanding the transcription factors that govern their expression, could eventually allow us to tackle such space-related physiological problems as bone and muscle atrophy at the genetic level. Our deepening understanding of biology at a systemic level could also pave the way for more radical strategies for extending human presence in space, such as for example inducing hypometabolic stasis in astronauts for long-term space flight.

4 Current Work Within the Advanced Concepts Team

The preliminary work completed to-date indicates that biomimetic engineering has considerable potential application to future ESA activity. Consequently there are several studies currently underway within the Advanced Concepts Team:

- Bionics and space system design general study
- EAP-based artificial muscles as alternative to space mechanisms
- Identification of possible human hibernation mechanisms
- Biologically inspired solutions for robotic surface mobility.

Additionally, future pilot studies are planned in areas such as:

- Organic/inorganic hybrid materials applied to space structures
- Long endurance flight study for atmospheric probe
- Proton collection for hydrogen generation
- Hibernaculum integration into life support
- Electronics immune response for increased failure tolerance
- Growing structures in space.

5 Summary

A short introduction to the potential application of biomimetic engineering in the arena of space exploration has been presented. Specific areas of high applicability have been identified, and existing work within these areas, along with possible avenues for future research presented. The preliminary work being conducted into biomimicry by the ACT has then been described.

Biomimetics is an already vast and growing area of research which covers a huge range of traditionally separate disciplines such as materials science and artificial intelligence, and there are strong reasons why biomimetic engineering could have significant application to space exploration. A dynamic and hostile environment, communication delays, impossibility of maintenance or resupply and a requirement for autonomous activity are all features of space missions that would benefit from a biomimetic response.

As engineered systems become more and more complex, it is understandable that they should begin to exhibit (or are required to in order to be effective) characteristics of biological systems. Taking a reductionist view of biological systems, they are an engineering response (performed under the same physical constraints that we as engineers face) that have allowed life to colonize and prosper in a huge range of terrestrial environments. The many problems that engineers face have already been solved by natural systems in many different ways. What is more nature is continually resolving these problems incrementally as conditions change. To be able to harness individual engineering concepts that come from nature has the potential to revolutionise the way we engineer future space systems. However, perhaps more exciting is the possibility to harness the fundamental evolutionary mechanisms that have driven the development of nature to such stunning levels of complexity and performance.

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