Biomimetics

– A new approach for space system design

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Biological systems represent millions of years of trial-and-error learning through natural selection according to the most stringent of metrics: survival. 'Biomimetics' may be defined as the practice of 'reverse engineering' ideas and concepts from nature and implementing them in a field of technology. This reverse engineering has recently attracted significant research due to an increasing realisation that many of the problems faced by engineers are similar to those already solved by nature.

ESA's Advanced Concepts Team views biomimetics as a means of finding new and realistic technologies for application in future space missions. The research is not concerned with mere imitation of biological systems, but rather focuses on understanding the fundamental processes and mechanisms used in nature, in order to discover promising concepts valuable to space engineering. Benefits are expected in areas as diverse as sensors, actuators, smart materials, locomotion, and autonomous operations.

Biomimetics

The success of biological organisms in solving problems encountered in their environments is attributed to the process of natural selection, whose primary metric is survival – failure implies extinction! Such biological solutions offer insights into alternative strategies for designing engineering systems. Biological systems represent millions of years (billions of years in the case of microbes) of trial-and-error learning through natural selection. Nature has implemented 550 million years of multi-cellular evolution, generating some 5-10 million species, of which only some 1.7 million have so far been catalogued. This represents a huge database of biologically-inspired solutions to problems. There is thus much that engineers can learn from biology and emulate in their design of engineering systems – this discipline is called 'biomimetics'.

Biomimetics involves 'reverse engineering' the principles of evolutionary design of biological organisms in order to implement biological solutions to general engineering problems. The problems encountered by biological systems are similar in many respects to those encountered in engineered systems. It seems appropriate therefore to examine biological solutions in order to analyse engineering issues. Research efforts in this direction have recently become significant in interdisciplinary-engineering topics.

Biomimetics Technology Tree

Structures and Materials	Structures	*Novel Structures* *Dynamic/adaptive Structures* *Deployment, Folding and Packing*
	Materials	*Composites* *Bio-Incorporated Composites* *Smart Materials*
Mechanisms and Processes	Mechanisms	*Muscles and Actuators* *Locomotion*
	Processes	*Novel Processes* *Thermal Management* *Fabrication* *Power Generation and Storage*
Behaviour and Control	Behaviour	*Classical Artificial Intelligence* *Behavioural Artificial Intelligence* *Learning Mechanisms* *Swarm Intelligence (DAI)*
	Control	*Reflexive Control* *Rhythmic Control*
Sensors and Communication	Sensors	*Vision* *Hearing* *Touch* *Taste and Smell*
	Communication	*Passive Group Communication*
Generational Biomimicry	Generational	*Ecological Mechanisms* *Genetic Mechanisms* *Cultural Mechanisms* *Geneering/Human Alteration*

Biomimetics Applied to Space Engineering

A spacecraft is designed to cope with a hostile and highly variable physical environment. Although it may not seem totally appropriate to examine biological organisms that have evolved in the terrestrial environment in order to seek novel solutions to problems encountered in space engineering, we seek not to replicate biological organisms *in toto*, but rather to abstract the biological principles by which organisms function and survive. The appropriate level of abstraction of such bio-inspiration is not a trivial issue. A successful example of already developed bio-inspired engineered solutions is represented by artificial neural networks used for control systems, which are highly simplified and re-structured abstractions of biological neural architectures.

Satisfying solutions

Engineers often seek optimal solutions in spacecraft and payload design. The process, which is generally very costly/time consuming, could benefit if 'satisfying solutions' are already known. Satisfying solutions represent the approach in biology whereby the historical constraints of available genetic resources lead to the evolution of organisms compliant with the prevailing environment.

Robustness and adaptability

Robustness and adaptability are particularly critical issues in space, as the environments to be explored are typically unknown and vary with unpredictable dynamics. The most sophisticated engineered systems are often lacking in robustness and adaptability, while simple natural organisms excel in terms of adaptability to their environment, actuation flexibility and sensory robustness. Ideas inspired by nature could therefore represent valuable solutions with regard to these issues.

Autonomy

Another critical issue for space systems is that of autonomy – the distances involved, particularly once spacecraft venture beyond Earth orbit, preclude real-time control, thus necessitating high degrees of onboard autonomy. Although autonomy is typically associated with exploration spacecraft, the issue of autonomy is also relevant to Earth-orbiting platforms, as ground-station-based control is the dominant factor in operational costs.

Biological organisms evolve, adapt and learn in highly variable environments whilst maintaining their functionality. They exhibit autonomy *par excellence*, and could therefore inspire new solutions for highly autonomous engineered systems.

Miniaturisation

Volume, mass and power are important and often critical parameters for spacecraft and their payloads. Their reduction implies several benefits, including significant cost savings.

Biomimetics applied to space engineering promises the prospect of greater miniaturisation, integration and packaging efficiency, which biological systems exhibit. This has natural synergies with micro-systems technology, which integrates electronics, mechanics and optics on a highly reduced scale to achieve high performance and high complexity within a very small volume (e.g. a few mm^3). An important consideration for such miniaturised systems is that their surface-area/volume ratio increases, and this has two important consequences: their power dissipation increases, requiring greater power volume density, and their structural strength increases, allowing greater loadings.

System design

A characteristic of natural systems is their holistic design. A more systematic adoption of biomimetics in space systems design could involve a new approach that treats a functional unit in a concurrent and multidisciplinary way. The payload of the spacecraft is thereby not treated separately, but as an integrated, indeed primary output of the space mission – its behaviour. The environment also acts as a feedback mechanism to the spacecraft. This provides the basis for the modular and hierarchical division of the spacecraft.

Implementing Concepts from Nature in Technological Fields

Reverse engineering of ideas and concepts from nature and implementing them in a particular technological field is not a straightforward process. There are a number of major differences between engineered products and biological systems when designing a bio-inspired system:*

1. Most organisms are characterised by cylindrical shapes and curved surfaces, while engineered structures generally have straight edges and sharp corners.
2. Engineered products are generally constructed from homogeneous materials, while biological materials are composites to a variety of degrees.
3. Engineered structures are designed for stiffness (and so tend to be brittle), while organisms favour strength over stiffness for toughness.
4. Biological features often have multi-functional roles.

When reverse-engineering concepts from nature and adopting biomimetic solutions, the following general caveats are proposed in order to obtain applicable engineering solutions:**

(i) Biomimetics may be a good starting point.
(ii) Pure biomimetic approaches can yield non-optimal performance solutions.
(iii) Sometimes optimal solutions result from traditional technology.
(iv) Biology relies heavily on good integration through the use of multifunctional structures.

A wide number of engineering disciplines could be analysed taking into account existing solutions adopted by nature, some of which are shown in the 'Biomimetics Technology Tree' on the facing page. Although this tree could be greatly

* From P. Husbands et al. (1998), *Connection Science*, pp. 185-210.

** From R. Michelson & M. Navqi (2003), Von Karman Institute for Fluid Dynamics Lecture Series.

expanded and extended, it can be used as a starting point for future studies and analyses.

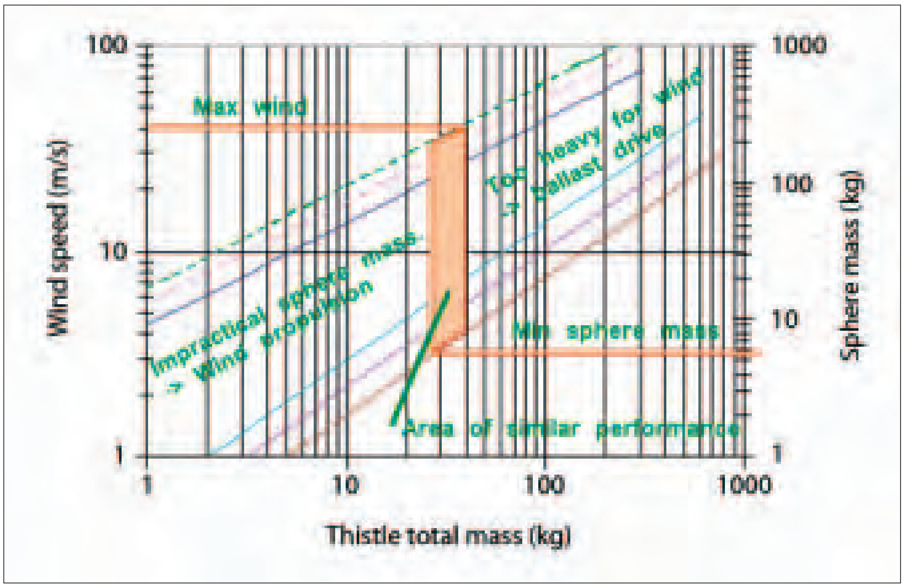
Research on Biomimetics

Considering the advantages of reverse-engineering concepts from nature and taking into account the major differences between engineered products and biological systems, ESA's Advanced Concepts Team has already analysed some bio-inspired systems for space applications.

Biologically inspired solutions for mobility

Mobility is one of the most interesting fields for bio-inspired space solutions. In nature, there exist several types of systems used for mobility in the air, on the ground, and in liquids. Dandelion seeds, maple seeds (see lead photo) and hoppers are just a few examples that have been considered for bio-inspired space system design.

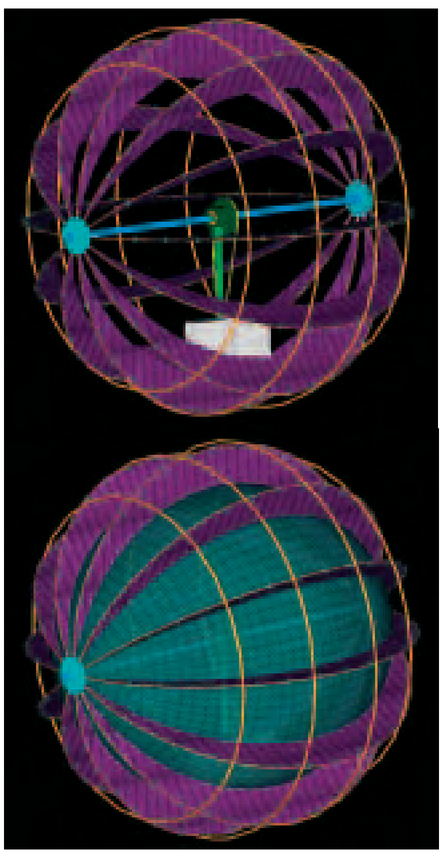
One design concept based on the Russian thistle was produced by the Helsinki University of Technology in collaboration with ESA's Advanced Concepts Team. While rolling in the wind, this thistle disperses its seeds (typically 250 000 per plant) over a wide area. Both passive wind propulsion and ballast-drive mechanisms were compared and interesting results were obtained, as shown in the accompanying figure.



Overlap in terms of similar performances for wind-propulsion and ballast-drive mechanisms

Maple seeds

Russian thistle caught on a barbed-wire fence. Image courtesy of DesertUSA.Com



A bio-inspired thistle-based design concept

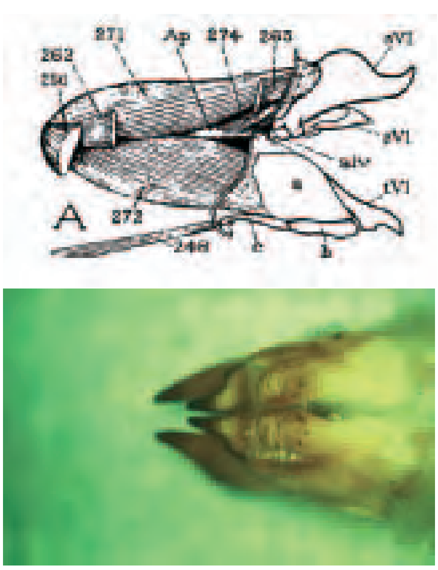
Considering the Mars surface environment as one potential application, particular attention was paid to ways in which natural energy sources could be harnessed (solar, wind, thermal, gravitational potential energy, etc.). In the bio-inspired thistle-based design concept shown here, the system, which has turbine blades and an external skeleton, may have an open (top figure) or a pressurised closed section (bottom figure). An optimal wind-turbine configuration would increase the efficiency of the system and perhaps include a ballast-drive mechanism for steering, overcoming obstacles, and actively moving the system to locations of scientific interest.

Digging mechanisms

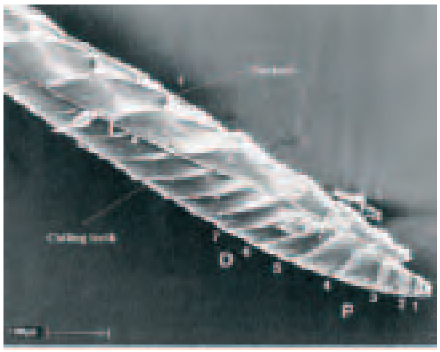
Natural digging mechanisms used by insects have also been investigated to identify techniques that space engineers could replicate to produce better surface diggers. Among the wide variety of such mechanisms in nature, two specific 'biological drills' have been studied in more detail.

The first are the ovipositor 'valves' of the female locust (analysed together with D'Appolonia, Italy, and the University of Bath, UK). Snodgrass presented his studies of the morphology of ovipositor valves in 1935. The upper sketch in the accompanying figure represents the digging mechanism of a typical grasshopper, while the lower image is a photograph of an ovipositor. The ovipositor valves open and close cyclically while the system moves up and down using different sets of muscles. The upper valve is used for excavation, whereas the lower one pulls the locust's abdomen down the hole. When the two valves are in their closed position, they are inclined by about 20 degrees with respect to the direction of the apodeme. This natural mechanism has been used as the basis for a digging mechanism design that was dynamically simulated as a concept for a miniaturised space drill.

The second digging mechanism was inspired by Sirex Noctilio, a type of wood wasp (analysed together with the Universities of Surrey and Bath, and EADS Astrium Ltd., UK), which uses a reciprocating motion to drill holes in trees into which it deposits its eggs. With this mechanism, it is able to drill at a rate of about 1-1.5 mm/min. The two valves, which slide longitudinally against each other, have backward-pointing teeth that allow the driller to move forward into the hole. In contrast to a conventional rotating drill, this system requires no external reaction force during drilling as the linear reaction forces required are generated within the pair of valves. A conceptual design for such a bio-inspired digger has been constructed to evaluate its feasibility for space applications. In particular an asteroid subsurface-sampling mission profile was considered, but the solution inspired by the Sirex Noctilio can potentially be employed in a wide variety of mission scenarios. Based on the asteroid micro-penetrator shown in the accompanying figure, the study confirmed the feasibility of applying the wasp-inspired concept to design a digging mechanism.



Above: morphology of the ovipositor valves and muscles of typical grasshoppers (from Snodgrass (1935), Smithsonian Institution). Below: photograph of an ovipositor



Sirex ovipositor digging mechanism (From J.F.V. Vincent & M.J. King (1995), Biomimetics, pp. 187-201; reproduced with the kind permission of Springer Science and Business Media)

While both of these systems show promise in terms of being novel digging designs, their potential benefits are still to be fully assessed through further investigations.

Artificial muscles

The development of electrically deforming materials, in particular Electro-Active Polymers (EAPs), has led to improvements in the performance of actuators designed to serve as 'artificial muscles'. Compared with conventional systems, these bio-inspired actuators are of interest for use in space systems because of their inherent compactness, lightness and ability to perform large displacements when an electric field is applied. In addition, these materials, when combined with unconventional biomimetic designs, could provide compelling solutions for complex problem areas.

Schematic of an asteroid micro-penetrator

Joint research work has been carried out by ESA's Advanced Concepts Team and other European research centres (Inter-departmental Research Centre 'E. Piaggio', University of Rome, Kayser Italia, and University of Reading, UK) to assess the potential of EAPs for space systems. A thorough investigation of the physical and chemical properties of the different classes of EAP showed that sensor/actuators based on dielectric effects are of particular interest for space applications. Dielectric EAPs can exert large forces and produce considerable displacements, making it possible to design high-performance actuators. A prototype linear electromechanical actuator made of a dielectric EAP developed by the 'E. Piaggio' Centre is shown in the accompanying figure.

Development of EAPs in fibre form is currently at an early stage, but is of particular interest because of the extra flexibility that they could bring to actuator design. Promising work is also being carried out on the use of dielectric EAPs in elastic energy-storage devices (e.g. as elastic springs). This combination could increase the maximum power delivery of these devices, allowing higher-velocity displacements. The performances of the EAPs themselves may also be improved through the use of anisotropic dielectric polymer-fibre systems, allowing greater strains for a given input.

Compared to the other classes of EAPs, however, dielectric electro-active polymers require high voltages, with the associated risk of electrical breakdown. This will have to be carefully considered for practical implementations, and especially in space applications where spacecraft safety is of primary importance.

Energy-storage structures

Although plants are not renowned for their mobility, some species are capable of rapid movements, especially when such essential functions as defence, nutrition and seed dispersal are involved. The leaf of the Venus flytrap plant is particularly interesting due to its ability to close up in a fraction of second. In the initial phase, whilst the leaf is still convex, its movement is quite slow. In a second phase, the leaf changes its curvature to become concave and performs about 60% of the displacement needed for closure in roughly 0.1 seconds. In the final closing phase, the leaf again moves slowly.

The behaviour of the Venus flytrap during its opening phase suggests that the system undergoes a redistribution of stresses, probably caused by changes in cell-wall stiffness and modifications to the turgor pressure. The leaf's motion during the opening phase also suggests that its elastic instability boundary is not crossed. Once the leaf opens again, it returns to the initial pre-strained state, accumulating the necessary elastic strain energy for another cycle.

Prototype of a linear Electro-Active Polymer (EAP) actuator

The Venus flytrap's behaviour has been analysed in the context of new space mechanisms and structures (with D'Appolonia, Italy and University of Bath, UK). A proposed engineering solution involves the use of shape-memory-alloy, hybridised fibre-thermoplastic laminates to obtain bi-stable tubular extendable systems. The structural, modal and stability analyses performed suggest that they could be used, for example, in jointless deployable mechanisms.

Hibernation and a possible human hypo-metabolic state

Human hibernation is one of the fascinating concepts that could enable astronauts to reach the farthest planets and moons of the Solar System and beyond, by reducing their life-support-system requirements during long-duration space flights. Given the compelling nature of this concept, ESA's Advanced Concepts Team has studied the technical feasibility of, and possible performance gains from this technology, with the help of biomedical scientists. There are many mammals, of at least six mammalian orders, which exhibit torpor. This torpor, which can be seasonal or non-seasonal, is characterised by a drastic reduction in body temperature. Also, when an animal is entering torpor, its heart and respiratory rates decrease, accompanied by a reduction in oxygen consumption. Physiological functions are kept to a minimum during torpor and the body is maintained at near-ambient temperature.

Several mechanisms could induce such a hypo-metabolic state in humans. The first involves a lowering of body temperature that could be achieved by changing its 'set-point' or lowering it directly, for example by inhibiting the shivering mechanism. Other mechanisms might effect a variation in the human metabolism or the modulation of cell-nucleus activity. One example of the latter involves the use of DADLE, an opiate derivative, which inhibits the activity of living cells. When injected into a rodent, the animal is considerably less active and its body temperature drops notably. Hydrogen sulphide has also been tested on house mice (non-hibernating species), inducing a harmless and reversible suspended-animation-like state. These successful experimental results suggest the possibility of medical applications. Regulation of gene expression is another mechanism that could potentially provide a means of inducing human hibernation, as evidenced by the ability of some seasonal animal hibernators to enter torpor in the absence of any environmental changes.

The induction of a hypo-metabolic state in humans would require the careful monitoring of such parameters as blood pressure, body temperature, respiratory rate and tremor, as well as electro-cardiograms, electro-encephalograms and electro-myograms. Special equipment would also be needed to induce, maintain, monitor and arouse the subject from a hypo-metabolic state. Nevertheless, the 'technology' remains potentially interesting for long-duration human space flight due to the possibility of significantly reducing the overall mass of the life-support systems needed.

While the studies that have been carried out so far show that we are far from being able to induce hypo-metabolic states in humans, and that even the processes involved are not well-understood, the relevant subject areas will continue to be monitored to constantly review the approach's feasibility in the light of scientific developments.

Future work and studies

To facilitate the transfer of biomimetic ideas from nature to space technology, a special database (www.bionics2space.org) is under construction. The aim is to link researchers in the biological and space-related fields by providing a resource that makes it easier for them to find and communicate bio-inspired solutions.

Current research is focusing on mechanical joints inspired by nature. New biomimetic designs have been produced that promise performance gains due to space and mass savings compared with conventional systems.

Behaviour and control is another area that can benefit from biomimetic studies (see table). Some bio-inspired algorithms have in fact already been developed by looking at natural mechanisms and processes. These studies, which are currently being carried out within the Advanced Concepts Team, will be further pursued in the near future with the help of experts in the field.

As biological micro-sensors and actuators (biologically sensitive mechano-receptors, campaniform sensilla, cilia, etc.) have the potential to be small, light and embedded in an ordinary structure, just as they are embedded in the bodies of insects, they will also be the subject of future research. This research could eventually lead to the design of new bio-inspired force sensors, strain sensors and distributed actuators for particle or fluid motion.

Conclusions

There are numerous instances of technology and mission requirements across most technical and service domains that could benefit from the application of biomimetics. They range in the technology domain from the potential application of bio-inspired artificial intelligence to onboard data-management systems, formation-flying control, deep-space navigation, rendezvous and docking. Biomimetic proprioceptors, biosensors and technologies such as electro-active polymers could also be considered for autonomous orbital systems, in support of life-sciences research. Biomimetics also has potential applications across several service domains, ranging from the use of biomimetic automation and data-fusion algorithms in Earth-observation systems, to biomimetic-based environmental control and life-support subsystems. As reported here, the first short studies aimed at assessing new bio-inspired concepts for European space systems have already been performed through joint collaborations between ESA's Advanced Concepts Team and European research centres. This fascinating domain of interdisciplinary research is already producing innovative ideas and conceptual solutions for the long-term development of space systems and subsystems.

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