

POTENTIAL BIOMIMETIC SPACE SYSTEMS ENABLED BY MICRO TECHNOLOGY

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ABSTRACT

Micro technology is thought to be enabling for biomimetics, allowing functionality at smaller scales, closer to those exhibited in many biological systems. In space engineering in general, the functionality permitted by microtechnology at lower mass and volume may provide great benefits to future missions. In addition to simple substitution of current systems, this benefit may be increased by utilising this generic lowering of mass and volume in novel, more effective and efficient systems. Many biological systems can be found that have attractive characteristics in comparison to current engineered systems. Since many of these are of small dimensions, such as systems in insects, biomimetics may be used to extrapolate aspects of ready miniaturised systems found in nature to apply in new systems for use in space. In this paper, we introduce the maturing engineering discipline of *biomimetics*, and its relation to both *space* and *microtechnology*. Some examples for areas of future study incorporating these three elements are given, in the context of current international research. Included in this section is detail of relevant past and current research by ESA's Advanced Concepts Team. The potential for such systems is discussed, highlighting the wide range of technology areas and levels of complexity in which solutions may be found.

BIOMIMETICS AND MICRO TECHNOLOGY FOR SPACE ENGINEERING

In the search for ever more efficiency and functionality, without sacrificing reliability or robustness, Biomimetics is emerging as a discipline which is increasingly seen as a source of novel concepts for new and improved technologies for space science [1].

Biomimetics is the practise of designing engineered systems, inspired by biological systems. The process of natural selection acts as a system of optimisation for organisms, such that many satisfying solutions exist in nature to allow species to survive. While the objectives for biological systems are generally different to those for engineered systems, biological

systems often excel in areas where engineers would like to improve [1,2,3].

Many novel uses of micro and nano technology in biomimetic space systems may be envisaged in the future. However, here we focus on a few areas of research that are currently established, both internationally and within ESA's Advanced Concepts Team (ACT). Several pre-designed miniaturised systems are present in nature, often with compellingly attractive characteristics. Micro technologies are seen as enabling for biomimetic systems, providing previously unachievable functions at small scale, enabling the design of miniaturised systems that may be able to take advantage of more aspects of small scale biological designs [2].

Clearly the main potential advantage in exploiting this synergy between Biomimetics and microtechnology would be the opportunity to reduce the mass and size of space systems, without compromising either reliability or functionality. Indeed, as functionality may even be increased through exploitation of particular properties of these technologies, implementation in space systems may enable entirely new mission architectures, a role that is also envisaged for biomimetic space systems.

International research in biomimetics is established and growing, this includes research in systems specifically for use in space, as well as generic research that has the potential for use in space. Examples of both, that will or could involve micro systems are given in this work.

Biomimetics is now an established part of work in ESA's Advanced Concepts Team, and is foreseen to continue to be for the near to medium term, given that the field is still maturing as an engineering discipline, and the breadth of possibilities for work in the field. With nanotechnology becoming a more prominent area of ACT activity, we hope that the synergies between these fields discussed in this paper will open new avenues in this research area, with a view to the combination of these fields becoming established in space engineering.

Broadly speaking, from 5 biological principles identified as being relevant to space systems design [4], MEMS technology was identified as having relevance to numbers 2, 3 and 4:

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

In addition, many specific areas were identified with reference to the ESA biomimetic technology tree [1], where microtechnology may be applied. This has been designed to provide a structured classification of ESA technology areas as they relate to biomimetics. Here, we summarise the potential applications of MST to relevant technology domains present in this structure [4].

Structures and Materials

Many structures in nature have attractive features for the biomimetic designer such as load optimisation, intelligent response to loading, novel deployment strategy and novel topologies. These structures are often exhibited at micro or nano scale, or require structure at these scales to perform their functions. The ability to manufacture such structures could potentially have impact in a wide range of space missions, saving mass and volume from component to system level, while perhaps increasing robustness.

Materials in nature may be found that have properties such as low loss of performance after damage or intelligent response to stimuli. These materials often rely on micro or nano scale structural elements to display these properties, although their effects are present at macro scale. Particular interests for small scale technology in space includes research in self-healing materials using hollow microfibres, and artificial muscles (e.g. electro active materials).

Mechanisms and Processes

With a wealth of ready miniaturised mechanisms present in nature, many novel and highly functional miniaturised mechanisms might be designed for use in space, utilising micro technology to enable implementation of these concepts at scales smaller than that which is possible using conventional technology. Bio-inspired joints [14, 18] or actuators could be enabling for many tasks involving other miniaturised systems. Mechanisms for locomotion, in particular, could inspire good solutions for miniaturised extraterrestrial rovers.

A range of biological processes at small scale are of interest to the space engineer. These include small scale physical processes such as cellular mechanisms for filtration and capillary action for heat transport. Processes for the manufacture of materials might lead to useful analogues in space applications.

Sensors and Communication

Biological systems for all five human senses have inspired research into potential engineered analogues. Different methods for implementing these senses can be found in other species as well, usually also requiring features at small scale.

Several different natural sensors are being investigated for biomimetic design, offering advantages such as integration in structural elements or miniaturisation. New functionality may even be gained through such study, for instance through the development of touch sensors to allow the characterisation of textures.

INTERNATIONAL RESEARCH

Interest in Biomimetics is growing for many applications where better solutions are sought. In this section we identify a few areas of research that have the potential to apply to Biomimetic space systems utilising micro technology.

In most of these areas, few biomimetic designs are developed at scales approaching that of the original system. Translation of principles used in a biological system are vital to the success of the biomimetic system, and doing this in the best way in any particular case is rarely an easy process. As the specifics of translation for these systems become more clear, and more MST systems are developed, the particular applications of MST will become more clear. In this section, we identify just a few of the areas where MST may be applied as an enabling technology.

Attaching Strategies

The ability to adhere surfaces, and being able to separate them simply afterwards, could have many possible applications in space. Exhibited, for instance, by geckos and spiders, the ability to support their own weight while standing on vertical surfaces, or even upside-down, is provided by nano/micro-scale structures on their feet. Van der Waals forces produced by hairs on their feet enable this effect, allowing robust, yet fast, mobility across challenging terrain. The gecko, uses the fact that a sheet of such hairs adhere strongly laterally and transversally, yet weakly when subjected to a peeling force, keeping their feet flat when they are to be stuck while being able to peel them off quickly to locomote [5,6]. This characteristic is analogous to the behaviour of Velcro, another technology with similarities to natural systems that is used in space.

On the other hand, biomimetic attaching grippers have been enabled by MST. For instance, a new generation of climbing robots is based on the use of miniaturized spines which are employed to anchor a robotic system to hard vertical surfaces [7,8].

Optics

Given the penetrating nature of x-rays, grazing incidence reflectors are generally used for x-ray optics. X-ray observatories using optics are generally limited to very small

fields of view – usually 1 degree or less [9]. X-ray emissions are important in the study of many astrophysical objects, and are often unpredictable in their time variability, which is in itself an important area of study. Ideally, therefore, x-ray observations should cover the whole sky to enable the observation of many sources over long periods of time[10].

Currently in development, a novel x-ray telescope involves an optical design based on lobster eyes to provide observation over a wide field of view with sensitivity suitable for observation of lower luminosity x-ray activity. Rather than using a refracting lens, a lobster's eye uses many reflecting channels to focus light. These channels are arranged in a spherical configuration so that a wide field of view is achieved. Similar to this, the LOBSTER-ISS all sky monitor uses a spherical configuration of small reflective channels to focus x-rays on a detector, enabling high sensitivity observation across a large field of view.

While this system is at macro scale, the biological system that is based on it is at micro scale. We might speculate, therefore, that other useful systems using such optics might be designed through use of microsystems. Certainly, one could identify several applications for micro-scale optical devices that offered high sensitivity across a wide field of view, offering an efficient method to observe a variable and unpredictable environment. In fact many novel, miniaturised optical systems may be found in nature, and enabling greater functionality at smaller scales may make designs based on them feasible for use in space [11].

Worldwide research has also focused on the analysis of other animals' vision systems. For instance, several research groups have investigated fly compound eyes and were also able to reproduce micro-scale synthetic samples with similar functionality and structure to those found in nature [12,13]. Miniaturized optical systems are of interest for space applications especially when integrated in micro-platforms for surveillance and exploration.

Novel locomotion for rovers

Conventional wheeled rovers for extraterrestrial exploration generally have limited mobility in rough terrain, and limited range. Some novel bio-inspired solutions have the potential to overcome some of these drawbacks.

Due to the conditions in Mars atmosphere, conventional fixed wing flying vehicles have several disadvantages in operation in comparison to earth's atmosphere. Issues affecting winged flight in this case are low Reynolds number, lack of oxygen for air-breathing propulsion, the low speed of sound and the low temperature. Among the consequences of this are that fixed wing vehicles must travel fast to create enough lift, making surface observations difficult, while rotors must spin slower, or have smaller diameter, to avoid problems when the wingtips break the sound barrier [26].

It has been found that insect flight also occurs in a low Reynolds number regime, from which it might be concluded that

biomimetic designs for Martian airborne rovers, based on winged insects, might produce efficient flying mechanisms with low speed, hovering, take-off and landing capability for Mars environment. While the mechanisms of insect flight are not completely understood, it is thought that the interaction of the flapping wings with the vortices that they create provides extra lift. A design named entomopter [22,26] is in the process of development, and is thought to have potential for use in Mars atmosphere. Based on the flight of the hawkmoth (*Manduca sexta*) a micro-flier suitable for Mars exploration is in development, which employs a reciprocating chemical muscle to provide propulsive power.

Hopping locomotion has also been studied as a means of accessing rough or sloping terrain on a surface [23]. Large coverage in rough terrain is allowed through use of impulsive mechanical propulsion, bypassing the problem of traversing challenging surfaces. With micro-scale design, large numbers of such rovers might be released at once, each with its own coverage area, to allow wide ranging, in situ science. To take another hopping mechanism example, the MINERVA probe, that was intended to land on the asteroid Itokawa, used an accelerating internal mass to provide propulsion [24].

Designed at small scale, miniaturised systems for payload and basic functionality will clearly be an enabling factor for such systems, reliant on maintenance of low mass [27].

Self healing materials

The ability of a material to autonomously retain or regain its useful properties after damage is clearly attractive, particularly in space, where intervention for repair is seldom possible. Biological systems often have this ability.

Of several concepts to bring self-healing capabilities to materials, one study that focused on space applications has developed a fibre composite with embedded hollow microfibres that contain healing agent [25]. When the material is damaged, some of these glass fibres break, releasing the agent.

The process itself may be one of several types. Fluids in different fibres may react and harden on contact with each other, or a substance may be present in the polymer matrix itself to cause or catalyse hardening. Promising early results have been shown for this approach, with experiments showing that the material can retain most of its strength after impact, compared to a conventional polymer composite.

A slightly different approach has been developed, with the use of microcapsules to contain the healing agent [25]. This approach has the advantage of potentially releasing the agent local to the damaged area, rather than releasing agent from a whole fibre when it is broken.

MST FOR BIOMIMETIC SPACE SYSTEMS IN THE ACT

The Advanced Concepts Team (ACT) of the European Space Agency (ESA) started working on biomimetic subjects on 2003 and immediately the value of using MST to design bio-inspired space systems for future use was highlighted. The results of early work, which is starting to be publicly available,

shows the potential of the combining of MST and Biomimetics to design novel space subsystems as mechanisms, sensors, actuators, optical systems, etc.

Micro digging systems

An example of the biomimetic approach is presented by the design of novel micro-drillers inspired by insects’ ovipositor systems [17]. In particular, the female locust and a species of wood wasp (*Sirex noctilio*) have been considered as interesting examples of natural micro digging systems. These two mechanisms have characteristics and advantages not found in conventionally engineered systems.

As regards the locust digging system, research has shown [19,20] that the ovipositor valves exert forces needed for digging independently, such that additional reaction force is not required from the rest of the animal. A three dimensional reconstruction of the mechanism’s mechanics is shown in Fig. 1 [17].

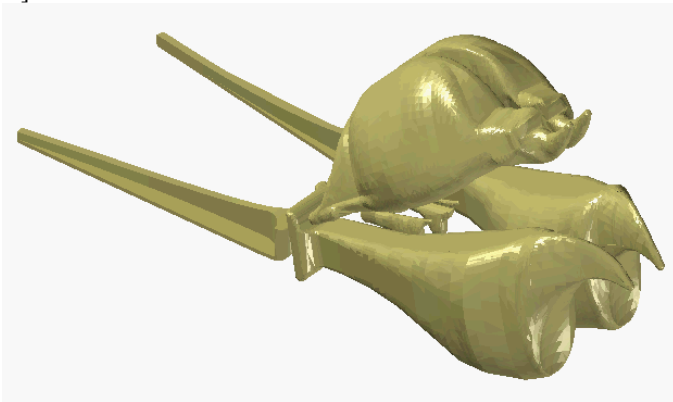


Fig. 1 Locust Digging system [17].

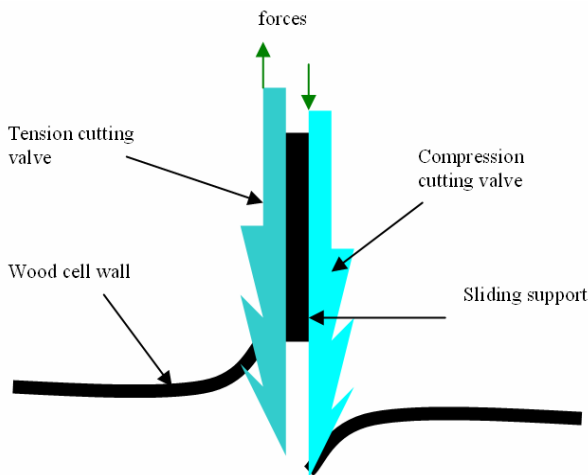


Fig. 2: Reciprocating motion of valves. Figure reported from [17]

As regards the wood wasp, the animal’s ovipositor digs using a longitudinal reciprocating motion of its two valves. While these valves slide against each other, backwards facing

teeth on one valve are employed to exert the reaction force needed to make the second valve penetrate into the wood (see Fig. 2). A cyclical repetition of this process allows the mechanism to drill into the wood without the need for external reaction force[17].

Both systems have been analysed from an engineering point of view. Macro-scale tests have been performed in order to better understand dynamic effects otherwise difficult to predict. The two systems have also been designed considering different available micro technologies.

There are quite a few possible space applications for these bio-inspired digging systems. They could be used in highly-integrated micro-systems equipped with micro-sensors, and micro-actuators, capable of communicating through optical or radio links and suitable for planetary exploration. Another space application concerns the use of a micro-driller as the main component of micro-moles for under-soil investigations. Arrays of micro-drillers could also be used as smart grip system to be embedded on wheeled and climbing mechanisms [17].

Micro strain sensors inspired by campaniform sensilla

Insects are able to control their posture and movements using proprioceptive sensors. Biological sensitive mechanoreceptors are inherently small, light and embedded in insect bodies. In particular, campaniform sensilla are used by insects as natural strain sensors. Cockroaches, for example, use sensilla to sense strain deformations and to determine both load and muscle forces.

Research into campaniform sensilla began in the 1960s [21] and preliminary electron microscope images showed that sensilla are connected to bipolar neurons. When the sensor is strained, a train of impulses is propagated to the central nerve system and insects can use these signals as feedback for their locomotion control.

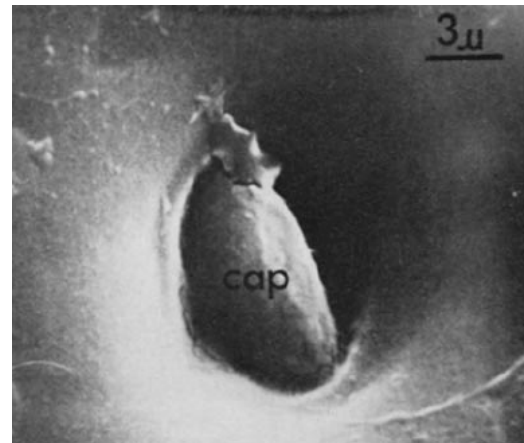


Fig. 3 Campaniform Sensilla. Reproduced from [21]

Embedded strain sensors are of interest for many space applications especially when light structures are used (solar

panels, booms, solar sails etc.) or when structural frames must be monitored during hazardous mission phases such as during launch and landing. Strain sensors can also be used as force sensors when, for example, they are embedded in cantilevers. Therefore, they may be suitable for use in unlocking systems, docking mechanisms, limit switch devices, robotic arms, etc.

The ACT has proposed and is currently leading a research activity aimed at assessing the feasibility of a micro strain sensor inspired by campaniform sensilla. After a careful review of natural campaniform sensillum sensors, the study is focusing on the design of a strain sensor that incorporates the main characteristics of the natural sensor. MST has been considered for the manufacture of these micro strain sensors. Preliminary results [15] seem promising although an industrial development programme is required to confirm the validity of a possible product.

Distributed actuators

Animals and plants have a wide variety of sensors and actuators customized for particular purposes and uses. Some bio-perceptive systems have the characteristic of being distributed along surfaces and not localized in small areas. This feature makes it possible to have efficient actuators that do not influence the shape or macroscopic characteristics of organs in which they are located. An example of distributed actuators concerns motile cilia that are almost never found alone and beat in coordinated waves attached to cell's surfaces. In nature, they are employed for several applications including the following. In the human trachea, for example, they sweep mucus and dirt out of the lungs. In the oviducts, the ovum is moved from the ovary to the uterus by means of cilia. Another example of a distributed mechanism is the peristaltic wave motion which enables the intestine to transport food.

Miniaturised actuators integrated on surfaces could have several applications in space domain. For example, they could be used for advanced delivery sampling systems where samples are transported and accurately positioned under scientific payloads by a surface which deforms in three-dimensional space.

A technology that the ACT is promoting together with the research center "E. Piaggio", concerns the use of dielectric electroactive polymers (buckling systems are shown in Fig. 4 [16]). The objective is to develop such a system in micro-scale in order to achieve fine positioning. A similar distributed actuator could also be used for the transport line of digging systems for extraterrestrial excavations. Dug soil could be carried to the surface (especially on bodies with low gravity fields), by a distributed actuated tube capable of performing peristaltic movements as our intestine does. This solution could be miniaturized with respect to traditional systems, providing an efficient new technology for use in space.

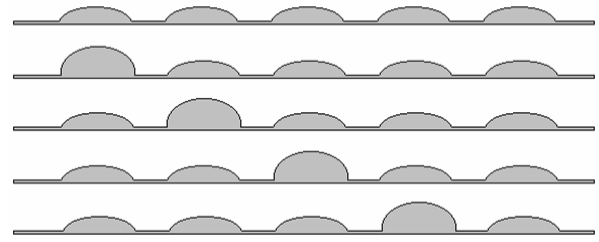


Fig. 4 Array of dielectric active polymer actuators. [16]

Bio-inspiration from plants' roots

Plants show good capabilities of looking for nutrients without the need of a complicated locomotion system. They can survive in very harsh environments and are able to successfully replicate themselves. Roots do not only anchor plants in soil, but are also capable of gathering signals with their embedded sensors. These signals are then transduced, processed and used for strategy control in order to find the optimal path for root's growth. Autonomous systems having adaptable, path-finding and intelligent micro roots equipped with actuators and integrated sensors are appealing for future studies and research.

Robust, lightweight and compact payloads capable of digging into the soil searching for past and present signs of life have potential application in space. Bio-mimicking the design of plants' roots could lead to the design of high-performance engineering systems suitable for space exploration. The readiness of micro technology now seems able to allow preliminary engineering studies and research in this challenging topic.

The ACT has recently initiated research in this field and, together with European research centers, novel interesting results are expected. Micro technology will play a primary role for the development of appealing new mechatronic explorers.

Attaching mechanisms and strategies inspired by Spiders' legs

Biological systems are capable of efficient operation and agile movement in unstructured environments. Their design combines several cooperating subsystems. Spiders can climb on vertical surfaces, upside-down, build webs and walk on them; some species even make use of tools. There are several

engineering prototypes of bio-spider systems but they are mainly based on macroscopic observations of the animal's design. A closer look at the particular micro features of the design of spider's attaching mechanisms together with a proper formulation of strategies used for their locomotion could lead to promising results.

Locomotion in space scenarios is of increasing interest for use in inhomogeneous environments encountered during exploration. Operation in EVA and IVA could also benefit from innovative systems efficiently moving on spacecraft surfaces without the need for structured pathways. Monitoring and inspection could be performed by miniaturised systems capable of autonomous movement and operation, while biomimicking spider design strategies. In addition, the possibility of walking on artificial webs deployed in space and/or to assemble space structures presents other interesting scenarios [28].

The objective of the study that the ACT is currently proposing is to investigate and develop micro systems which bio-mimic the attaching mechanisms of spiders. This mechanism enables spiders to walk over a diverse range of surfaces and environments. For this purpose, many spiders have adhesive systems (scopulae hairs), miniaturized tarsal claws and serrated bristles at their tarsal tips that guarantee a high level of mobility and grasping capabilities on a variety of surfaces. This research is aimed at proposing an innovative concept for a bio-inspired attaching mechanism, taking into account suitable micro-nano technology processes.

CONCLUSIONS

Having presented a selection of examples from state of the art international research, we have shown that potential biomimetic space systems using MST are beginning to attract research effort across a range of space related technological areas, worldwide. Collaborative studies have shown that there are numerous areas where these three fields, biomimetics, space engineering and MST, may find common ground in creating new solutions. Further examples suggest areas in which current research does not encompass these three fields, but perhaps has the potential to do so. The bio-mimetic approach, though relatively new, has already led to promising results, some of which are summarised here, reinforcing its feasibility and usefulness for space engineering.

Given the range of space technology areas in which applications might arise from MST enabled biomimetic space systems, from simple to unusually complex, potential customers could come from anywhere in the space industry, in the case of simple, easily integrated solutions. The more unconventional or risky solutions produced by these methods are usually considered by national or international space agencies, who find that potential benefits are great enough to warrant investment.

This broad set of possibilities also gives rise to a wide range of potential costs, with very simple systems potentially having

low development, implementation and manufacture costs, while enabling cost savings at mission level with mass savings, for example.

On the other hand, while potentially being offset with increased mass efficiency and functionality, some of the examples of more complex biomimetic designs given above will require substantial investment for further development. Much further work is needed before any of the systems presented here can find uses in space, and of course biomimetic systems using MST may only come into use as MST itself is established as space technology.

So far, the work in biomimetics performed by the Advanced Concepts Team in collaboration with European academia has been in an initial phase of growth, with focused research since 2003. Results so far have been promising and with nanotechnology becoming another major area of ACT research in the near future, it is expected that the areas of crossover as illustrated above will lead to new collaborations, internally as well as in collaboration with European universities

By fostering research in this manner, and in particular by focusing on the uses of MNT in more detail, the authors expect that systems, designed through biomimetics and utilising MNT, will become important in designing better space systems in the future.

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