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BIOMIMETIC APPROACH TO ADVANCED SPACE MISSIONS

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ABSTRACT

This paper proposes and discusses the use of a biomimetic approach to conceive and design novel advanced space technological systems. The paper analyses the different phases of space missions, namely launch, parking, transfer, landing and exploration, and investigates possible advantages of a biomimetic approach for each of them. Bio-inspired technologies currently used in the space field are pointed out and new biomimetic concepts are proposed to conceive new space systems and subsystems both for the short- and long-term future.

Keywords: Biomimetics, Space Exploration, Bio-inspiration, Autonomy.

INTRODUCTION

More than a century ago, an enthusiastic young man systematically analysed the functional properties of birds' wings. By transferring gained knowledge into technical design, he became one of the founding fathers of modern aviation. Although Otto Lilienthal [1] did not call his approach biomimetics, it is an exemplary masterpiece of what this rather new scientific field attempts to do in a systematic way. The combination of thoroughly studying natural beings for their technical properties and the subsequent transfer of these findings to applied disciplines can lead to both a broadened understanding of biological systems and an improved design of engineering products. Not only industry, but also space communities are about to appreciate the impact that such an approach of ‘reverse engineering’ [2] might have for mid- and long-term prospects and advanced technological developments, suitable to face the new challenges emerging with the future exploration to the edge of the Solar System and beyond.

Key areas of promising bio-inspired space applications, as diverse as sensors, actuators, smart materials, locomotion and autonomy, have recently been identified [2,3] assessments of biomimetic research for space exploration and system design have been carried out [2], and convenient methodologies elaborated [4].

Aiming at outlining the practicability of biomimetics as an engineering tool for future space exploration and indicating possible development trends, this paper considers the phases of a typical exploration mission: launch, cruise, landing, and exploration. For each phase, its basic requirements are shortly outlined, currently applied biomimetic technologies identified, and further, some new technologies in progress, and those that might be expected in a future, are introduced and assessed.

1. LAUNCH

The launch phase is very critical for the mechanical structure of the space system as it undergoes high static and dynamic loads. These loads are mainly due to excitations of the propulsion system and aerodynamic effects, peaking at the lift-off from the pad and during the transonic flight. Ariane 5, e.g., induces steady state accelerations in the longitudinal axis up to 4.5g with a sinusoidal vibration level at the base of the spacecraft up to 1g in the frequency range of 5-100Hz [5]. Random vibrations and shocks during the separation of the stages should also be accounted for in the design to prevent failure. To withstand the structural loads imposed by the launch, especially load bearing components should have high natural frequencies to avoid coupling with the resonant frequencies of the launcher, and geometries that minimize the concentration of stress should be considered.

Current spacecraft have already incorporated some components that have been inspired by designs found in nature; e.g., spacecraft panels often show the special topology of honeycomb structures [6]. As described in [7], laminated metallic or polymeric structures arranged in cellular honeycomb patterns offer high structural strength at relatively low weight. They demonstrate excellent capabilities of load support, attenuating high intensity dynamic loads as created by impacts of pressure impulses, thermal cycling, or intense acoustic blast waves. When cracks form, force fields are diffused throughout the entire structure, thus allowing for good energy absorption, stopping further crack propagation. Offering increased resistance to the penetration by ballistic projectiles [7], in particular, several studies have also been focused on the protective damping capabilities of laminated honeycomb panels with respect to debris impact [8] as often used on the outer side of satellites.

Bioinspired research towards new concepts for an improved launch phase is focusing on atmospheric resistance with positive effects on savings of combustible and thermal loads. The streamlined body contours of swimming penguins, for instance, perfectly deal with varying streaming conditions of the surrounded medium for effortless swimming, or in a broader sense, for propulsion through fluids at minimized energetic expenses, which is of compelling interest for aeronautic, marine, and space technology.

As another example, the natural principles of load flux dependent design, as means of self-organisation and proactive damage prevention, exemplarily demonstrated by growing trees or bones, might inspire future structural technologies for launch vehicles. The strategy behind, i.e. isotropic load distribution throughout the structure, is explained in the case of trees by differential growth rates of wood, growing faster where highly stressed and structural reinforcement is needed while growth is slowed down in regions of lower stress. However, this irreversible process is proceeding on an extended time-line. Bone growth on the other hand shows better dynamics appropriately redistributing bone material upon local load situation, i.e., supporting material is either accumulated or removed. But, although current research on biomimetic self-healing reveals first advances [9], the capabilities are very limited, far from practical maturity. In near or mid-term future, the virtual mechanism of load-adaptive growth behaviour cannot be technologically mimicked, whereas bio-inspired models of tree optimization are already derived and transferred to applicable technology [10]. Following these guidelines, computational methodologies and algorithms for optimized design of critical parts have been developed. Alike trees, minimized amounts of material and optimized stress distribution are balanced, and, the load path flux is gently guided throughout the geometry.

Another potential technology that could be used during structural and vibration testing relies on the inspiration of campaniform sensilla of arthropods that are able detecting displacements of 1 nm. The system relies on the mechanical amplification of structural deformations that allow improving measurement's precision. Bio-inspired strain sensors could be used as indirect force measurements as arthropods do. Results of analytic models suggest promising outcomes for future engineering applications [11].

2. TRANSFER AND PARKING ORBIT

Space environment is extremely harsh, and accordingly spacecraft and their payloads should be designed for extended lifetime as repairing in space is generally not an option. Outgassing occurs in vacuum, material properties deteriorate and optics could become irreversibly dirty and occluded by aggregation of ultrafine dust particles [12]. Only lubricants at solid state are generally allowed, and this is often an issue also because friction in vacuum generally increases. In addition, atomic oxygen encountered at orbital altitudes can modify surface structure properties compromising spacecraft thermal control. Radiation and fluxes of high energetic plasma is also a challenge for electronics as degradation and Single Event Effects can occur [13]. Protection from debris is another key aspect to be carefully considered; shielding using light and smart material is currently a topic of deep investigation. The design of thermal radiation systems is also very particular for spacecraft – solar radiation, albedo, planetary and spacecraft's own emissions have important roles in the design of passive and active thermal systems.

Several technologies inspired by nature are currently used. Artificial muscles, i.e. thin wires of Shape Memory Alloys, are used in different applications as e.g. in unlocking mechanisms. In order to avoid lubricants and degradation effects due to friction forces, biomimetic compliant mechanisms like inflatable gossamer or hydraulic closed-loop systems [14] have been conceived and studied. For mission analyses and trajectory design, bio-inspired optimization algorithms, such as genetic algorithm, particle swarm optimization and ant colony algorithms, are already extensively applied, as reviewed in [3].

Once arriving on orbit, the deployment phase of the mission starts. In view of the design of large deployable or inflatable space structures like solar cells, beams, or antenna arrays, biological folding and deployment mechanisms [15] are highly compelling due to their unequalled packing efficiency. However, thermal deformation can induce non-negligible stress and misbalances that can determine poor performance of the payload, and malfunctioning of bearings and mechanisms, leading possible failures of the entire structure in the worst case. Continuous health monitoring of space system deformations is therefore of interest especially when counter-measures can be taken. Aiming at addressing these issues and initiated by the authors, several systematically biomimetic studies toward more reliable and robust space architectures, such as arthropod-inspired deformation sensors [11] for distributed sensory networks or innovative articulation concepts [14,16], are in progress and first promising results have been published.

To ensure operational robustness of space systems, functional maintenance implies both the development of self-healing composites [9] and suitable architectures for autonomous health monitoring, self-diagnosis and self-healing in synergy with routines and control architectures based on classical and biomimetic AI methods. In particular, failure tolerant reconfigurable neural networks and generic algorithms have been suggested as efficient ways to anticipatory and proactive behaviour, mimicking the process of biological learning [3].

Closely related to the latter, the perceptive efficiency of many biological vision systems along with their high capabilities of neural information processing and feature extraction stimulate a variety of engineering concepts spanning a wide range of near-future space applications from recognition, tracking, inspection and monitoring tasks to vision-based navigation [17]. Inspired by lobster eye optics, a new concept of an all-sky X-ray monitor telescope is currently being studied. Lobster-ISS is proposed to be flown to the ISS around 2009/2010 to be attached on the External Payload Facility on ESA’s Columbus module [18].

Several new other technologies for the future could be conceived by taking inspiration from nature. For instance, photonic IR sensors for the detection of electromagnetic radiation from infrared to ultraviolet have been evolved in so-called pyrophilous insects [19]. For the detection of forest fires, *Melanophila acuminate* beetles carry special antennal smoke detectors and thoracic IR receptors that even detect source intensities as low as 60 pW/cm² [20]. Pit vipers have similar organs; but latest investigations rather identified those pits as highly sensitive (10^{-3} °C) broadband thermal detectors. [21]. In both species, the organs’ low thermal mass and rapid heat dissipation permit high temporal and spatial resolution of thermal stimuli. In comparison with conventional uncooled microbolometers, IR-sensilla are advantageous in speed and sensitivity, ease of design, working even at high ambient temperatures and harsh conditions without the need of vacuum. Very recently, microelectromechanical (MEMS) sensors for IR detection have been developed and proof-of-concept testing performed [20].

For manned missions long transfers are extremely challenging as humans need constant ambient conditions in order to survive. The Advanced Concepts Team has investigated the possibility to mimic the hibernation behaviour of mammalians (e.g. *Spermophilus tridecemlinneatus*) [22].

3. LANDING

During the landing phase, the descending probe, lander and payloads experience mechanical loads such as vibrations and shock impacts. In addition, the design is thermally challenged, especially in case the targeted celestial body has an atmosphere. On top of that, autonomous navigation, descent stabilization, no-shock landing, and reliable and compact deployable mechanisms contribute to mission success.

In the present state, landing systems often decelerate using parachutes and finally airbags during the different stages of descent. Strong winds or heavy vibrations may induce possibly fatal instable situations, e.g., the parachute could collapse. In this context, autonomous, bio-inspired landing systems may lead to a less vulnerable design, although mimicking manoeuvres of birds and insects may seem too demanding. However, a variety of simple gliders may already perform appropriately. At first, there are passive gliders, usually found in plant seeds. Dandelion seeds get airborne and use a self-stabilising parachute-like design that will not collapse in turbulent airflow. A second example would be, e.g., airborne maple seeds which by their shape start rotating like a propeller, slowing down the descent. The basic morphological design but not the breaking principle of maple seeds is reflected in a glider-concept by the Jet Propulsion Laboratory [23]. The general advantage of passive gliders lies in their simple but effective design. Although, there is no control possible and landing sites cannot be chosen nor obstacles avoided, in missions with numerous identical small and simple landers, such a passive system may be beneficial, whereas singular and more fragile spacecraft need an actively controlled (but still autonomous) descending system. Biological examples are some ant species that jump off high branches and use their hind legs to actively steer back to the tree stem [24]. As "wings" they use their hind legs, which display flattened limb segments. More obvious and rather robust gliders are Mediterranean cockroaches (e.g. *Blatta orientalis*). In contrast to the American species, only males have wings and these are rather rigid and short compared to those of flying insects. Consequently, they cannot fly; but, when falling off an elevated spot, they do use their wings to decelerate and steer, quickly choosing an appropriate landing site, controlling the flight via visual and airflow sensors. Integrating the technical and the control architecture of gliding cockroaches may lead to a more reliable system for planetary descent.

While there is already work undergoing concerning the technical transfer of visual auto-piloting of flying insects [25], mimicking the mechanical design of insect wings both used for flying and gliding is still at an early stage. Insect wings are lightweight structures using different ways of deployment (one time inflation and hardening vs. multiple events of folding and unfolding), the structural folding of the flat wing allows for lift generation without using a voluminous profile [26]. In general, the cuticle of arthropods provides a great source of inspiration: It is the biological analogue to a multifunctional fiber/matrix material compound. Being an exoskeleton, it aids at impact damping and protecting the animal's organs. Being a material continuum, it integrates tough areas for force transduction as well as flexible (joints) and elastic ones (energy storage, damping) within only a few micrometers. In the context of a bio-inspired lander, especially the arthropod cuticle's functions of shock-absorption and damping are highly interesting. But for solely damping, there is no need mimicking the entire cuticular material and structural arrangement, since there exist several systems of mechanical damping in biological organisms. While grasses and trees (and the before mentioned insect wings) have to cope with oscillations, there is also a variety of structures adapted to withstand strong impacts, such as shell structures of marine animals, or shells of nuts and coconuts. Due to its high sensitivity to mechanical impacts, in particular the brain of mammals is protected by a series of dampers, one of which realized in the entire design of the skull.

Right after landing, it is critical to gain secure anchoring in the ground. Again, nature gives an intriguing example: plants anchor the ground in a rather unique way compared to state-of-the-art technical devices [27]. In a slow but effective and energy saving way plant roots expand, reacting towards gravity, humidity and external forces. A technical adaptation of the plants' rooting processes could facilitate autonomous and scalable anchoring of planetary landers, and by using in-situ resources also payload could be significantly reduced. Subsequent deployment of permanent structures could be inspired not only by plant leafs [28] but also by the mechanisms insects inflate and harden their fragile wings after hatching [29].

4. EXPLORATION

The exploration of new celestial bodies is mainly driven by the quest for signatures of present or past life. Rovers, robotic and autonomous exploratory systems shall perform in situ sample analysis and other scientific operations, preparing subsequent human missions. Payload requirements for this purpose are very demanding as scientists need as much information as possible provided by compact and light systems to fulfil mission specifications. Main challenges concern the generation of energy and the protection of payloads and delicate components from the harsh environment, namely from the large range of temperature variation, possible dust storms, corrosive atmospheres, etc. Another key issue to be tackled with is autonomous path planning and locomotion, as scouts should ideally be able to overcome any possible obstacle and explore any area of the body.

The basic task of planetary explorers to probe the ground at various locations already involves a variety of complex sub-tasks, generally including the collection of subsurface samples. The standard approach of drilling holes in the ground is not really welcome as it involves the application of high external forces and the use of heavy and bulky machinery. However, the mechanisms used by insects to probe various substrates, usually to lay eggs or to extract food samples, are completely different from those hitherto known. The drill (i.e. the ovipositor) of wood wasps (*Sirex noctilio*) consists of two interlocked pieces that do not revolt but move along each other with the tip shaped in a way that it rather pulls itself actively in the ground [30]. Another main issue, locomotion, has been subject of many studies (e.g. on the reversible adhesion to smooth surfaces: [31]). In principle, legged locomotion would be a desirable means but also the by far most complex approach. Other natural systems have been studied and tumbleweed turned out to be an interesting model for low energy propulsion [32]. Moreover, the structure is deployable and flexible; hence, it concurrently protects the core from heavy impacts. Bio-inspired studies are also focusing on mimicking active flapping flight. There is a variety of ongoing research projects on deepening the knowledge of biological systems [33] and promising attempts of transferring this knowledge to technical design.

Exploring unknown environments is the basic task of foraging animals, being even more valid in social insects such as bees, wasps, and ants. These insects actually start foraging excursions from a fixed point of reference, the nest or hive, whereto they return later. *Cataglyphis* ants are among the most fascinating species in terms of animal navigation as they are faced with a bundle of constraints: they dwell in deserts, especially in the hottest and driest parts and feed mainly on other insects that have succumbed to these conditions. Accordingly, ants cannot use odour trails, nor recruitment, and even using visual landmarks is not always possible. The heating of their bodies also limits the exposition time to the Sun and hence speed is another critical parameter. Therefore, ants employ vector navigation, i.e. they integrate each segment of their path run (distance, direction, inclination) and constantly update their home vector, which is the direct path back to the nest [34]. This fascinating model organism has been well examined in the past and first attempts for technical transfer have been undertaken successfully [35]. Having a rather small brain of 0.1 mg mass, the neuronal control architecture involved in navigational tasks will use only a small set of simple but mandatory and sufficient algorithms, as it would be desired for a successful autonomous navigator for planetary missions.

The sensory mechanisms employed during navigation and locomotion are also of great interest. First of all, there is the performance of the compound eyes and the ocelli. Although the spatial resolution is only in the range of kilopixels, the analysis of visual data allows for monitoring self-movement, discrimination between far and close objects, and to detect possible predators or obstacles to be avoided. Next to the visual system, mechanosensory cues are essential during exploration. Again, insects and arthropods show amazing capabilities despite their reduced computational power [36].

The insects' body should usually remain free of dirt but sensors and wings are especially challenged by particles threatening to reduce their performance. Particle repellent coverings of transparent wing membranes [37] or the anti-reflecting microstructures found on the eyes of hawkmoths [38] are examples of biological surface microstructurisation with obvious potential for space applications.

But even if individual animals forage individually, we see some kind of inter-individual coordination. In desert ants, aggression in the individual is coupled with the vector state, or say, the distance from the nest [39] but there are also wars between entire colonies where communal decisions have to be taken. The discipline of swarm robotics [3] examines how communal actions are decided upon without a clear hierarchy be in place. The conceptual transfer for swarm satellites and distributed control is on the way.

5. CONCLUSIONS

Space system design is extremely challenging due to the harsh conditions dictated by a multiform space environment these systems will need to cope with on long interplanetary missions. Considering the special requirements of the different mission phases, by analyzing and assessing currently used biomimetic technologies, such under development, and also novel ideas that could be beneficially implemented, this paper illustrates how systematically applied biomimetics could leverage future space technology, bringing such exploratory missions a decisive step closer to reality.

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