Biomimetics and robotics for space applications: challenges and emerging technologies

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***Abstract* - This paper presents novel emerging robotic technologies for space applications conceived by reverse engineering ideas from nature. Although plant and animal species have evolved in the terrestrial environment, we believe that there is compelling potential for taking inspiration from nature to conceive novel, high-performance robotic systems for space use. This paper highlights the advantages that a biomimetic approach could lead and presents concept designs of innovative bio-inspired mechatronic systems investigated in recent years by the authors.**

Index Terms – Biomimetics, Robotics, Mechatronics, Space, Emerging Technologies

I Introduction

While further exploration of space is planned to involve an increase in human missions, robotic exploration will continue to play a vital role in complementing and supporting such endeavors. Presently, robots are used to support astronauts in extra-vehicular activities and they will soon be applied to assist them in intra-vehicular activities as well. In the space sector, improvement of the performance of robotic systems has a remarkable impact on the overall mission cost, such that the development of high-performance robots is particularly desirable.

Features found in natural systems such as adaptability, autonomy, reliability, miniaturization, etc. are currently studied to discover novel avenues of development for future robotic systems. Different communities and national and international networks have been formed in recent years to strengthen interdisciplinary research into bio-inspired robotics. However, little biomimetic research has been performed with the aim of solving realistic issues of engineering systems operating in the demanding and constrained space environment.

This paper presents our research performed in the field of biomimetic space robotics and is structured as follows: section II briefly introduces the challenges of space environments; section III discusses and inquires into the suitability of a biomimetic approach for space system design; section IV presents the prospects for research in space robotics whereas section V briefly introduces the special issues presented by this field; section VI presents results of bio-inspired robotic concept designs; section VII proposes two novel promising and compelling biomimetic studies for future development.

II The challenging space environment

In comparison to many terrestrial environments, space poses specific challenges and constraints to robotic systems. Particular differing physical factors range from the radiation and atomic oxygen environment in Earth orbits to harsh extraterrestrial environments in the form of extreme atmospheric conditions. Not only do these factors require mitigation through appropriate design, but also their effects are compounded by the fact that most space robotic systems have little chance to be repaired once in situ, thus making their reliability and robustness of paramount importance. That space-borne robotic systems are relatively isolated, with respect to the impact on the mission of required communication with terrestrial operators, further motivates the implementation of autonomous capabilities. The requirements for these capabilities may be demanding, given that such systems must operate robustly in unpredictable or unstructured environments, hence a high degree of adaptability is desirable to ensure proper functionality under many possible circumstances. Furthermore, with future missions perhaps involving networks of discrete robotic agents, greater abilities in terms of autonomous communication and cooperation will be enabling.

Perhaps the greatest issue for space systems derives from the high cost of access to space. Lower costs can often be achieved through reduction in mass, volume and power consumption. However, achieving such reductions often requires trade-offs in terms of robustness and reliability.

III Biomimetics: A useful methodology for space research?

A common statement supporting the usefulness of biomimetics in engineering is that biological organisms face many of the same challenges as engineering systems do. Space presents an environment radically different from that faced by all known organisms, such that biomimetics might be thought to be inapplicable at first glance. However, it can be seen that while direct analogies between space systems and biological organisms might be less common, many species exhibit qualities that are highly desirable in space system design, such as robustness, light weight, low volume and power, autonomy, adaptability and self-repair. In some cases, it may be seen that biomimetic solutions can even take advantage of the peculiarities of extraterrestrial environments in novel ways (e.g. Martian atmospheric conditions allow consideration of passively propelled rovers inspired by tumbleweed [1] and insect-inspired flapping flight [2]).

Previous studies performed by the authors in collaboration with academic and industrial partners, have highlighted several fields of space technology development where biomimetics might be profitably applied [3]. Of the broad categories identified in these studies, those with direct relevance to space robotics are materials and structures, mechanisms and processes, sensors and communication, and behavior and control. This wide interest in biomimetics in space motivates the continuing growth of biomimetics as an increasingly systematic and distinct discipline for the design of novel, high-performance space systems.

IV PROSPECTS FOR ROBOTICS IN SPACE

Most space agencies carry out programs focusing on space exploration for both scientific and strategic reasons. Exploration in space needs systems with a high degree of autonomy as tele-operation is expensive, and control loops for remote control must face long distances over which commands and telemetry communication travel. Launching systems into space that are capable of adaptation and autonomous decision-making would be an important asset in upcoming exploratory missions. So far, there are no more autonomous systems than human beings and exploratory missions can greatly benefit from their presence. However, humans are a result of the long evolutionary process that took place on Earth, whereas astronaut survival in space can only be achieved through meeting stringent engineering requirements. Equipment and provisions must be provided in space, astronauts must continuously train to prevent physical deterioration and psychological issues should be prevented or mitigated. The resulting financial outlays involved in performing space exploration with humans are therefore often prohibitive, especially for long-duration missions. In addition, exploratory missions are inherently risky as the environment is by definition not fully known. The high risk of losing astronauts' lives precludes their presence in most path finding missions.

Instead, the use of robotic systems in space exploration is often needed. Machines can be designed to withstand the harsh space environment for an extended time with some degree of autonomy and their loss does not have ethical implications. In addition, robotic missions are much less expensive than human missions, and long journeys can be undertaken with very little maintenance, and as life support equipment and supplies are not needed, mass and volume can be kept comparatively small.

However, in many ways robotic agents are not as efficient, autonomous or intelligent as simple natural organisms. A biomimetic approach is therefore an obvious way to improve the design of artificial systems. Recent studies have adopted this approach and focused on reverse engineering ideas from nature for application in space systems in order to obtain self-repairing, self-healing [4], autonomous, energy-efficient and intelligent space platforms.

V ISSUES CONCERNING RESEARCH IN THE SPACE SECTOR

Reliability is paramount for space systems as maintenance or repair is generally not an option. Reliable systems are usually simple, and rigorously tested. Established and simple technologies are therefore often used, as they have already demonstrated reliability. Transfer of proven technologies from other engineering disciplines to the space domain is therefore a common alternative to development of dedicated systems.

Robotics is a rapidly growing field of research for space, and impressive results have already been obtained, promising many of the performance advantages discussed in the previous section. However, high-performance robotic systems are intrinsically complex and are often built with new technologies in order to guarantee mass and volume savings; hence, critical issues concerning reliability arise. In the context of space, perceived and even actual reliability of technologies and systems is often reliant on extensive use in previous space systems. In recent years, there has been vigorous debate within space agencies on the financing of advanced and basic research in robotics, in large part due to these reliability issues.

VI PROMISING RESEARCH PERFORMED

In the subsequent sections, some bio-inspired robotic systems, which have been analyzed and studied by the authors and are relevant for space applications, are presented and discussed.

A. Gecko-inspired robotic systems

The gecko is an excellent example of a natural system capable of walking and running vertically and upside-down on a variety of surfaces. Two characteristics of this animal particularly attract the attention of researchers and scientists: its adhesion mechanism and its locomotion system. Adhesion and locomotion are thought to be coupled, and therefore an interdisciplinary study is requested.

The applications of a gecko-inspired robot are multifold in space. Its main characteristics are: 1) autonomy, 2) agility, 3) capability to overcome almost any kind of obstacle, 4) miniaturized dimensions. In addition, it has been shown that geckos are capable of exerting high adhesion forces mainly generated by molecular interactions such as van der Waals forces [5]. Gecko feet exhibit the highest density of surface hairs found so far among animal species [6]. Dry adhesion is based on contact splitting [7], i.e. the division of the contact area into an enormously increased number of single contact points between the micro-hairs and the substrate, generating strong adhesion [6].

Passive operation, micro-technological feasibility, and negligible dependence on substrate surfaces and environmental conditions, including space vacuum, make gecko inspired adhesives potentially superior to common robotic attachment systems (synthetic dry adhesives have been tested in vacuum chambers [8]). In this context, biomorphic low power rovers for in situ probes, and robots for intra- and extravehicular monitoring and maintenance of spacecraft, space stations or satellites, where conventional methods of attachment like suction or electromagnetism fail, are undoubtedly promising. In particular, robotic inspections of critical subsystems for environment control, life support, etc., would release astronauts from risky operations. The potentially small dimensions of gecko-inspired robots could also allow consideration of fleets of miniaturised agents with swarm intelligence (high redundancy implies high reliability).

The approach of the research performed was to synergistically study both attachment and locomotion systems of the gecko and take inspiration from the underlying fundamental principles analysed to design novel robotic prototypes [8]. Following the biomimetic approach presented in [9], the research started from a high level of abstraction and then gradually converged to a lower level of abstraction. Prototypes showed the feasibility of the concept design illustrating the potential of this bio-inspired system for space applications.

Current and future research is focusing on a variety of aspects. Biologists and physicists are debating the effects that environment induces on the performance of the natural adhesive, while engineers specialized in nano-technology are testing dry-adhesives based on carbon nano-tubes. Hybrid systems that take advantage of the compliant characteristics of gecko hairs and use of magnetic forces are also being analysed [10].

B. Spider actuators

Most animals and insects actuate their limbs with antagonistically arranged pairs of muscles: flexors and extensors. In spiders, however, the femur-patella and tibia-metatarsal joint are exceptional, as both possess flexors but lack extensors, which are instead substituted by a hydraulic system. Their legs are movably suspended from a central body, the prosoma. When the prosoma contracts, the hemolymph flows through the spider's legs, which thereby straighten. Main features of this peculiar system are: 1) the prosoma acts as a pump which is contracted by linear actuators (the muscles); 2) the hydraulic system can be considered to be a closed loop system – it is completely sealed; 3) the force/mass ratio is high [11]; 4) the system is miniaturized.

The characteristic of the natural system which is particularly appealing to space engineers is the possibility to have a high force actuator embedded in joints. The main concern is the use of a liquid as working fluid – in space, outgassing is a common issue for liquid systems. In the natural system, however, the fluid remains in a sealed circuit and leakages do not occur.

The four main features mentioned above have been considered in the design of a novel actuator. Simulations have been performed and the model was validated through experimental results of a prototype. The conceived system has three main components: 1) a thin (0.1 mm) metallic foil which acts as a spring; 2) modular spacers that are attached to the metallic foil; 3) two miniaturized tubes that are located between the spacers.

The modular configuration of the system allows large rotations of linear behaviour: the value of the pressure inside the tube is proportional to the rotation of the joint. Each single joint of the simple prototype shown in Fig. 1 bends about 1.8 degrees when the pressure of the working fluid is set to 1.2 MPa.

Future work will concern the integration of the system shown in Fig. 1 with a pump inspired by the spider prosoma. Engineering solutions for the actuators include the use of smart materials such as piezo-electrics or electro-active polymers. A complete closed system might have the potential to be a competitive system for future space use, especially if miniaturised.

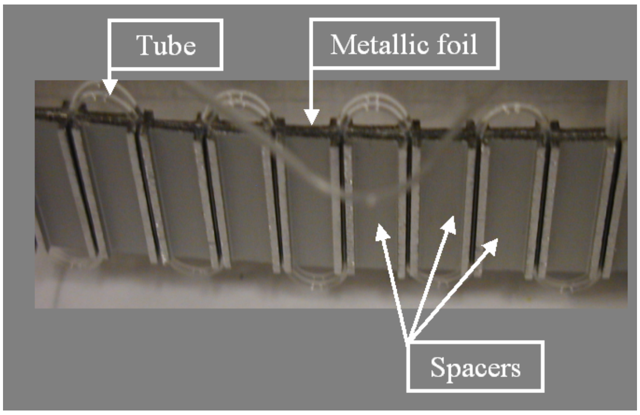

Fig. 1: Prototype of the spider inspired actuator [11].

C. Bio-inspired joints

Biological systems are unique in their capacity to combine a variety of tasks from walking to complex motor tasks such as grasping or dexterous manipulation. In articulated systems, joints are common failure points and their design is of utmost concern. Weight and dimension must be minimised (especially in space applications), while their reliability and functionality must be maximised. Furthermore, lubrication is a real issue in space mechanisms as the outgassing phenomenon prevents the use of liquids. In addition, friction significantly increases – several failures in the past were due to mechanism malfunctioning.

We performed two conceptual studies aimed at finding inspiration from natural systems. The first took a multi-disciplinary approach and investigated pros and cons of a large number of natural systems. The second study was focused on a specific joint, the human knee. Both studies are discussed in the following sections.

C.1.Exoskeletal joint

The detailed analysis of natural joints was mainly focused on 1) hydroskeletons, which allow different types of motion without the need of a structural skeleton; 2) exoskeletons, which have a closed skeletal structure that flexes at the point where articulation is required; 3) endoskeletons, which feature inner rigid elements supporting the natural system.

To improve reliability and miniaturisation of autonomous robotic systems, we focused on exoskeletal joints of arthropods where regions of gradual stiffness variation in a rigid cuticular frame passively define their mobility. Hence, their compactness, requiring neither sliding elements nor bearings and lubricants, allows for good structural integration. Merging these considerations, an active mechanism composed of a bellows-type outer structure (exoskeleton) with helix Shape Memory Alloy (SMA) actuators (artificial muscles) inside was conceived [12]. In the 2-DoF experimental prototype (Fig. 2), for simplicity, the bellows was replaced by a helically wound compression spring of similar properties, which was not torsion-stiff. Bending angles up to 10 degrees, and thus a workspace of 20 degrees, could be achieved. Analytical simulations of simplified 2D models indicate that with an appropriate design trade-off between workspace and joint stiffness a theoretical workspace of 75 degrees can be achieved which, however, will mainly depend on the specific application. The same system is also suitable to have 3-DoF (rotation around two axes and displacement along the vertical symmetric axis). In this case, the actuation should be provided by at least three linear actuators.

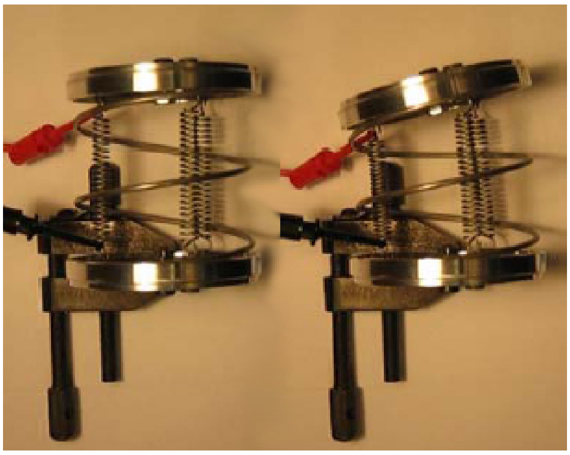

Fig. 2: Experimental set-up of a mechatronic joint before (left) and after one of the internal SMA springs was heated with a 2 A current (right) [12].

Although problems related to design, optimisation and controllability are still to be solved, we foresee an increasing demand and much potential in designing novel, structurally integrated articulation systems that not only permit optimised, energy-efficient and smooth trajectories, but also a high degree of controllable compliance and intrinsic failure tolerance towards both external and internal disturbances.

C.2. Knee inspired joint

Several bio-mechanical studies have been performed on the human knee joint due to its peculiar characteristics. We focused on a bioinspired approach aimed at designing a novel mechanism with high performance.

From a kinematic point of view, the knee joint can be represented as a compact parallel mechanism. Parallel mechanisms are of interest for current space applications as their high stiffness guarantees high precision. Three families of 2-DoF passive mechanisms have been conceived as described in [13]. An optimisation based on the use of clustering methods was performed, and allowed identification of an optimal mechanism geometry that can be scaled through simple analytical equations.

Deployable configurations were also conceived as launch vehicle dimensions constrain the launch dimensions of space systems. Tether-based systems have been considered as well to minimise the mechanism's weight and increase its workspace.

An engineering design was conceived in order to compare the concept with existing 2-DoF joints where, in particular, the Pancam Mast Assembly of the Mars Exploration Rover Mission [14] was considered as a reference. Simulations have shown that savings in mass could be gained by using a deployable parallel structure.

Future work will mainly concern the study of compliant elements in the bioinspired parallel mechanism. These have the advantage of not requiring lubricant and bearing systems, therefore both performance and useful lifetime of the mechanism could be improved.

D. Strain sensors inspired by campaniform sensilla

Motion control systems of insects are highly miniaturised and extremely efficient. While leg proprioception provides the necessary feedback for posture, limb position and reflexive control [15] specific strain sensors (so-called campaniform sensilla) measure strain-induced deformation as an integrated result from internal and external loads acting on the exoskeleton [16]. Anatomically, a campaniform sensillum is an elliptical hole extending through the outer cuticle with a bell-shaped cap or plaque suspended in its centre. In response to deformational loads, the hole changes its dimensions causing the thin cap to move up and down, exciting a nerve cell attached beneath the cuticle. This simple but extremely sensitive mechanism of strain amplification is capable of detecting displacements in the order of 1 nm [17].

Space environments impose high degrees of uncertainty and unpredictability on any dynamically working system. Besides mechanical stress, also thermo-elastic deformation has to be accounted for. Ideally, to ensure robust and safe operation, such distributed passive micro-sensory networks could be implemented to monitor structural states.

To illustrate the effect of strain amplification of cuticule hole deformation, a finite element analysis of an array of elliptical holes in a plate, mimicking the arrangement of sensilla at the base of fly's haltere (tiny club-shaped protrusions from behind the wings acting as gyroscopes during flight), was conducted. It was found that the major axis was not very sensitive to applied deformation, but the minor axis showed remarkable strain magnification [18], indicating directional load sensitivity. Analytical results confirm that strain can be derived merely by detecting load-dependent changes in the shapes of the hole. Due to the possibility of integration into composite structures, this method is thought to be appealing and worth further investigation. Future work should above all address issues such as the effect of elliptical aspect ratios on sensitivity and mechanical properties of the base material, effects of hole orientation on directional selectivity, and mutual interference of grouped neighbouring holes.

A variety of different strain sensors (commonly sensing force and torque) are in principle practicable in space; but, for each of them, ranging from simple conductive, capacitive, and electro-optical methods to contactless camera imaging, specific trade-offs and limiting drawbacks must be considered [18]. Embedded insect-like strain sensors are not only of interest for state monitoring of inflatable or slender mechanisms and structural frames, but also biomorphic exploratory scouts, and tasks involving fine motor control, in which robotic manipulator devices and their end-effectors are touching, grasping and/or manipulating delicate objects, or require precise force-feedback for adaptive behaviour.

E. Particle transport inspired by peristaltic motion

Nature offers a wide range of efficient systems related to particle transport and locomotion driven by actuators that are distributed on or embedded within the structure. An extremely versatile example thereof is peristaltic motion. Peristalsis is originated by wave-like propagation of successive muscular contractions that are employed to perform actions such as propulsion and mixing of food passing through the gastrointestinal tract, or as a means of locomotion in the case of earthworms that cyclically coordinate the contraction of antagonistic pairs of circumferentially and longitudinally arranged muscles along their individual body segments to move forward.

Peristalsis can inspire many potential solutions in modern space robotic systems. Available state-of-the-art technologies for systems applied to in situ sample positioning and transport, particle conveyance from soil excavation, or distributed peristaltic pumps for active fluid transport and thermal control could gain in functionality and efficiency without added complexity, for example [19]. By reducing the number of components, weight and volume, arrays of structurally integrated actuators might increase the total reliability of the entire space system.

Recent assessments showed that for many actuation tasks dielectric elastomer actuators are suitable candidates, owing to their repeatable and reliable high performance and durability ([19], [20]), coping with harsh space conditions. Focusing on novel distributed engineering systems and taking into account present technology readiness, three bio-inspired peristaltic concepts have been conceived, their basic feasibility analysed and experimentally confirmed by means of discrete prototype units [19]. A tubular structure of serially coupled, peristaltically expanding and contracting unitary modules of dielectric elastomer actuators fabricated in helical [21] or cylindrical [22] configuration seems to be the most versatile design as it theoretically allows both directed particle transport inside the hollow tube (mimicking an oesophagus) and locomotion (inchworm principle). All proposed concepts are currently being investigated with finite element analysis and advanced prototyping.

As suggested in [19], peristalsis might be well applicable for space robotic subsystems, e.g., manipulators inspired by elephants' trunk [23] that could be composed of a series of the tubular muscle units we are investigating. Since objects of many dimensions can be picked up, held and positioned simply by enveloping them, there is no need for gripping end-effectors as in the case of conventional manipulators [23]. Additionally, compliant design allows unequalledmanoeuvrability in reaching any point of the workspace quickly and in an energy efficient manner. Smaller objects or surface samples could be enveloped by sleeve-like end-effectors and peristaltically conveyed inside them, an approach that could also be applicable in autonomous subsurface exploration to minimise complexity of traditional soil excavation systems [24]. Simulations thereto are ongoing. We also assume that peristaltic elements on wheels of robotic rovers might improve their adaptability to surface textures, thus enhancing mobility and position accuracy [19]. Finally, undulatory locomotion of earthworms for propulsion through soil, as intensively studied in endoscopy [25], would be highly relevant for autonomous inspection tasks of tubular space systems and for subsurface penetration and exploration.

F. Bio-inspired digging mechanisms

Digging and sampling systems have been employed regularly in space missions. However, available digging techniques can be split into several categories with broadly applicable advantages and disadvantages. For instance, conventional rotary drilling systems tend to lead to high masses in space systems, though modern designs mitigate this characteristic and the technique can be applied to a wide range of substrates ([1], [24]).

Ready-miniaturised digging systems may be found in nature, and in the insect world in particular. Two such systems were selected for detailed study, having been found to have additional qualitatively attractive features in relation to conventional digging systems, in addition to their small size. These were the ovipositor of the female locust and the ovipositor of sirex noctilio, a kind of woodwasp. Analogous engineering systems may have the potential to provide efficient digging or sampling capability to future robotic extra-terrestrial missions.

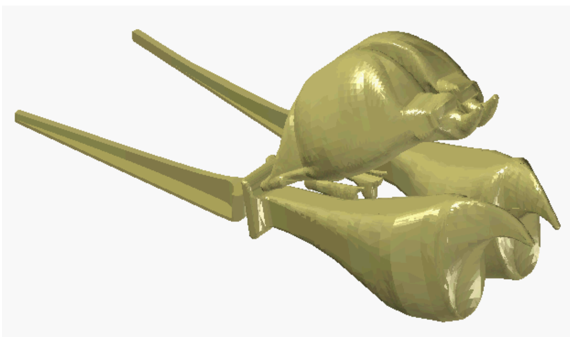

Fig. 3: 3D model of the locust digging valves [26].

Fig. 3 shows a 3D representation of locust ovipositor valves. This principle part of the digging system is connected to the animal by means of an extendable abdomen and actuation mechanism. The geometry of the system means that when the valves are cyclically swung open and closed, one valve provides reaction force required for the other valve to excavate soil, while also driving the mechanism deeper into the substrate ([24], [27]).

The woodwasp ovipositor, on the other hand, employs a longitudinal cyclical motion with its twin valves. Teeth on these valves alternately provide the reaction force required for drilling by the other valve. These teeth become pockets on different sides of the valves that enable waste to be transported up the hole [28]. Fig. 4 illustrates a simplified view of the digging process.

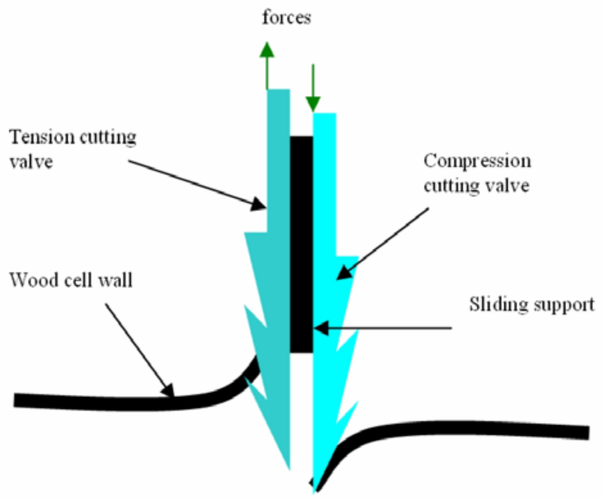

Fig. 4: Simplified model of ovipositor drill [28].

Engineering designs utilising concepts from these biological systems underwent initial analysis in collaboration between the authors and teams comprising members from industry and academia ([1], [29]). Numerical simulation and prototyping were employed in quantitative assessment of several concept designs, which took various degrees of inspiration from their biological counterparts. Numerical modelling and simulation of the locust-based design at micro scale suggested that such a system might be suitable for digging through granular soil, whereas the force required for substrate failure in cohesive soil is higher. A low cost macro-scale analogue was constructed in the case of the woodwasp-inspired design, resulting in an initial system found to be suitable for percussive drilling techniques.

Relevant micro-fabrication techniques were considered for the manufacture of components analogous to woodwasp valves in assessment of the potential of manufacture of comparable systems [24].

Miniaturised drilling or sampling systems based on these concepts show promise in a number of identified applications, though practical implementation in a robotic space system is clearly a long term goal. The most immediate requirement for the development of these systems is a breadboard phase, where integration of micro-scale actuators with the appropriate digging components will be a critical task [24].

VII PROMISING RESEARCH PROPOSED

Promising research that the authors are fostering includes two new biologically inspired concept-level studies: the attachment strategies of spiders and the soil exploratory capabilities of plants' roots.

A. Spider attaching mechanism

Owing to their extremely versatile and adaptive attachment mechanisms, spiders exhibit a large variety of locomotive strategies among their lineages. Some aptly walk sideways and backwards, climb on vertical surfaces, or even upside-down, while others stride on water or build webs on which they can move with impressive agility [30].

The tarsal attachment apparatus consists of two large claws and species-specific hairy ventral attachment pads. The claws grip on rough surfaces, whereas the hairs cling on smooth ones, and web spiders have an additional middle hook to grasp the silk thread [30]. In combination, high mobility and grasping capabilities on a large variety of surfaces are guaranteed.

Forthcoming studies will mainly be focused on the design of the microscopic attachment system, which provides spiders with an extremely adaptable and reliable mechanism. Spiders combine dry adhesion, as displayed by geckos (see section VI A), with versatile grasping capabilities. They are capable of efficient locomotion on webs through the synergistic combination of attachment capabilities and motion strategies. No miniaturized robots are currently capable of mimicking spider behaviour in this way.

There are a large number of scenarios in which spider inspired robots could operate. One particular application concerns their use for the deployment of large structures or for walking on artificial webs in space. As sketched in Fig. 5, robots crawl out of a centralized mother satellite and move on the triangular net towards the small daughter satellites at the corners [31].

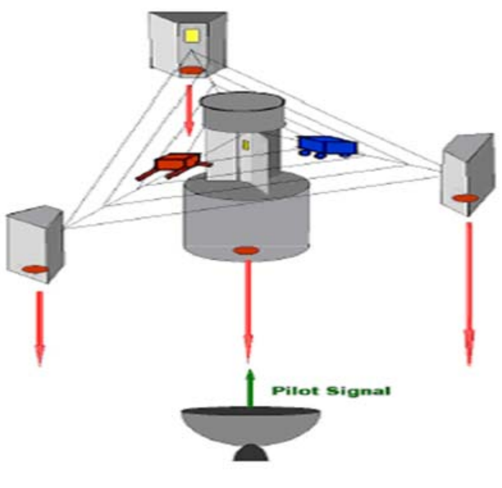

Fig. 5: Artistic view of a deployed space web and robots moving on it (Reproduced from [31], with permission).

Research into spider locomotion and attachment strategies is expected to lead to innovative solutions that meet the strict requirements for the design of a new generation of successful space agents.

B. Plant root inspired robotic systems

Plants' roots not only firmly anchor plants, they also actively explore all types of soils to feed plants with mineral nutrients and water. During this process, driven by tropic stimuli, roots gather signals and communicate with their rhizospheric environment ([32], [33]) following the optimal path for growth since plants do not exhibit active locomotion. This optimal path is dependent on local ambient conditions and the mechanical soil impedance [34], ramifying primary and/or widespread fibrous root systems form.

We are presently assessing the feasibility and technical applicability of the smart and adaptive path-finding and soil penetration strategies ([34], [35]) of plants' roots in collaboration with ARTS and CRIM Laboratories of the Scuola Superiore Sant'Anna in Pisa, Italy, and with the International Laboratory of Plant Neurobiology of the University of Florence, Italy, which have been awarded to collaborate with the Advanced Concepts Team in the framework of the Ariadna program of ESA.

Mimicking their holistic design and mechanisms of polar (directed) growth could be a prospective starting point for the design of autonomous, light-weight and self-optimising space systems. We see the most promising field of application in robotic planetary exploration and exobiology missions with the objective of characterizing biological and geophysical environments and identifying hazards for future human missions.

Compared to current drilling methods designed for space use [24], root-like, soil-penetrating robotic probes could be favourable in terms of low power consumption and autonomous decision-taking, detecting gradients of water, minerals, or hints of metabolic activity while avoiding areas of potential dangers. Communication networks with neighbouring probes could be established to convey gathered information and coordinate inter-agent collaboration, finally generating local 3D subsurface maps. Moreover, In Situ Resources Utilisation (ISRU) scenarios, i.e., the possibilities of energy storage, recovery, or extraction from the regolith soil, might be addressed by root-inspired systems. Detailed studies are needed for assessing realistic advantages.

Although artificial roots might operate in deep soils of celestial bodies, shielded from degrading cosmic agents, their possible functional design is extremely demanding. However, the readiness of micro technology might allow preliminary engineering studies and research into this challenging topic. To the best of the authors' knowledge, no artificial system mimicking growing plant roots has been proposed for space use.

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