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Bionics & Space System Design Project Progress Report for ESA Advanced Concepts Team

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INTRODUCTION

We are working on the ESA Bionics and Space System Design contract AO/1-4469/03/NL/SFe. The project is to review the application of biomimetics to space missions. Our particular focus is on robotic activities with an emphasis on planetary exploration. At the time of ASTRA conference, we will be preparing the submission of WP3, which most significantly includes the suitability of biological principles to robotics, specifically with respect to those that can be used for planetary exploration. This includes overall vehicle locomotion, biomimetic actuators/muscles, and materials that have biological characteristics. However, at the time of paper submission, we have only completed the WP1 portion of the contract and it will be discussed here.

PROJECT OVERVIEW AND CONTRACT OBJECTIVES

As contracted by ESA, the team is required to submit several Work Packages to support the research and projects relating to biomimetics around the world, both in-work and upcoming, as well as a proposal for future biomimetic robotics planetary exploration missions. Below is a simplified explanation of the requirements of each work package:

WP1 – Review of Literature and Ongoing Research Projects

In this WP, the team has performed a survey of the field of Biomimicry, listing and providing a brief description of key research work and literature, people and teams in Europe (especially in ESA Member States), Canada and elsewhere, and key programmes (international, national, government and industrial). Technical Note 1 is the deliverable which includes an assessment of European and worldwide biomimicry research and prospective areas of development.

WP2 – Identification of Space Technology Areas and Systems Categories

WP2 has been completed by ESA's Advanced Concept Team (ACT). The goal of WP2 was to make an inventory of space-related technology areas (in line with ESA Technology Master Plan) that are expected to benefit from the application of the biomimetic approach. The subjects addressed in this WP include functions, materials, mechanisms, architectures, approaches and/or methodologies, at the system (e.g. spacecraft) and/or subsystem (e.g. thermal control) level.

In addition, a certain number of generic systems will be identified as "test cases" in order to limit the scope of the remaining WP's and to focus subsequent research efforts. These design case studies include manned/unmanned interplanetary spacecraft, planetary surface systems, Low Earth Orbit satellite constellations, ground support facilities, and more. The final choice of the systems being addressed will be made during the study.

WP3 – Identification of Biological principles for Application to Space Systems

In WP3, the team is reviewing the suitability of biological principles and their application to space missions. The purpose is to identify whether any of these principles might hold potential for application to the design of space systems or provide solutions to space-related technical challenges. In WP1, the focus was general biomimicry, not necessarily with specific reference to space system applications. In this WP, space systems is the main focus and benefits therein and shall be categorised in accordance with the aspects of systems and technology areas identified in WP2.

The team is providing a preliminary assessment of the suitable biological principles with a view to ascertaining issues such as: whether and how such principles could be used for planetary exploration and long duration spaceflight; what new materials, structures and systems can be created from biological properties and principles specifically for spacecraft structures and components; and what new technologies, techniques and knowledge might be required to adapt any of the identified biological principles to create new spacecraft systems or components. The emphasis is on robotic planetary exploration missions primarily. The Technical Note 3 Biomimetic Principles Assessment Document is almost complete and provides a reasoned assessment of the innovative mechanisms, systems, devices, designs, configurations and the like found in nature's diverse life forms and used to provide technical solutions to problems and design cases identified during WP2.

WP4 – Detailed Assessment of Selected Biomimetic Design Cases

The final Work Package applies the space systems and technological challenges identified in WP2 and the suitability of various biological principles and solutions proposed in WP3 to the selection and conceptualisation of design case studies for innovative space system design. The pre-selected design cases include three biomimetic vehicles: one flying, one walking, and one digging. Each design case will be a valid conceptual design (up to Phase A level) for planetary exploration as the design team deems appropriate and includes a definition of the intended environments, maturity of the technology used in the design, and benefits resulting from the application of a biomimetic engineering approach.

WORK PACKAGE 1 – THE APPLICATION OF BIOMIMETICS TO SPACE ROBOTICS

Work Package 1 was recently completed with inputs collected over the first 4 months of the contract. This document comprised of a wide range of the benefits of biomimetics to the advance of robotics from institutions around the world. Examples were collected from a breakdown in over a dozen "subsystems" and the team organised them in such a way that both engineers and biologists/zoologists alike can understand.

Biological Modularity& Pleiotropy

The first aspect of biomimetics in its potential application to spacecraft engineering that we consider is the issue of systems design. Our prime concern here is the issue of modularity (and hierarchical structuring). Modularity and hierarchical organisation is a fundamental approach in both science and engineering as the means for problem reduction, necessary for complex systems.

Modularity is central to cognitive psychology models of human information processing. Specialised modules are attributed to certain functions of the human mind whereby human information processes are characterised by a signal flow of transduction, modular input systems, and a generalised central system. Cognition represents the organisation of an organism's behaviour within the environment. Cognition comprises a number of independent neural modules, each with separate functions operating on different principles; however, there are also cognitive processes that are different manifestations of the same general-purpose neural processing system (Fodor's thesis) [5]. Special purpose (domain-specific) modules also exist for the processing of perceptual information and coordinating motor responses as interfaces to the real world. Each module is functionally distinct. Other capabilities however are general manifestations of the same processes, eg. memory, problem solving, reasoning as these abilities overlap in their fundamental operation.

Biomimetic Materials

Biological materials and structures are characterised by multiple levels of organisation which impart toughness and multi-functionality in comparison with more traditional engineering materials. Biological materials possess their unique characteristics by virtue of their organisation rather than their material substrate. They are adaptable with the capacity to sense aspects of the environment and react accordingly – they incorporate "smartness" to their structure by integrating aspects of control. The use of natural materials for engineered structures is not completely unknown – the British Mosquito bomber of World War II was constructed primarily with wood making it very lightweight and fast while affording resistance to impacting gunfire. Wood possesses resistance to crack propagation initiated by impact by virtue of its cellular microstructure [8]. Cellular compartmentalism within structures is the approach exploited in honeycomb panels for spacecraft primary structures.

Most biological materials are soft with stiffness imparted through mechanical rigidisation by fluid pressure or through viscosity changes in gel materials – the biological analogue to electrorheological fluids. They are generally compliant with low Young's modulus and provide strength for resistance to breakage rather than stiffness for resistance to deformation. Composite materials are ubiquitous in biological systems in which the structure incorporates sensors, processors and actuators [13]. Most biological materials are composites comprising polymer fibres embedded within matrix materials – like engineered composites, their physical properties are highly anisotropic.

Shape memory alloys exhibit thermoelastic behaviour changes such that they can exist in two temperature-dependent crystal phases separated by phase change transitions. The most common shape memory alloy is the Ni-Ti alloy known as Nitinol (other examples include Cu-Zn-Al and Cu-Al-Ni alloys). The first such metal alloy discovered was Cu-Zn in 1938, but subsequent emphasis has been on Nitinol (Nickel-Titanium Naval Ordnance Laboratory). When plastically deformed in the low temperature thermoelastic martensitic phase, the alloy will return to its original shape reversibly by heating above a characteristic temperature to the austenitic phase (which is tailorable between 0-100^{o}C) and if restrained from regaining its memory shape will induce stresses of ~700 MPa. Shape change can occur over very small temperature ranges through the transition temperature. The transformation temperature range can be varied by adjusting the amounts of the constituent alloys.

Biomimetic Structures, Mechanisms & Deployables

Biological material is typically "soft" with structural stiffness commonly imparted through mechanical rigidisation of fluid pressure (turgor). Mechanical loads in biological organisms are carried by carbon-based polymer fibres – cellulose in plants and collagen in animals. The macromolecular chains are sometimes twisted into fibrillar structures with high modulus stabilised by side groups (resembling nylon, aramid and polyethylene artificial fibres). Like engineered composites, their physical properties are highly anisotropic offering stiffness and strength matched to the direction of the applied load. The fibres are bonded within a matrix (similar to engineered fibre composites) of polysaccharides, polyphenols or buckling resistant minerals such as calcium carbonate or hydroxyapatite. Fibres can carry only tensile loads as they are prone to buckling when exposed to compressive loads – when used in composites, the matrix does not contribute to load-bearing. Biological systems often overcome this deficiency by pre-stressing them to impart tension. Fluid pressure is used in non-woody plant cells and soft animals to pre-stress fibres to provide the structure with resistance to compression. Cytoskeletons comprise chains of proteins which give cells their shape, movement and structural integrity.

Plant leaves can react to environmental conditions such as tracking the sun (phototaxis). Leaf structures may be packaged and then deployed which have applications in the deployment of antennas and solar panels (eg. solar power satellites). Osmotic pressure in plant cell walls provides the basis for such actuation mechanisms. Although the osmotic pressure is low, it is amplified by the storage of elastic energy in the cellulose structure. Insects adopt a similar strategy to store energy in resilin within the cuticle to drive their wingbeats during flight. Spiders transmit hydraulic pressure in their blood by compressing their bodies to extend their legs.

The traditional approach to structural design has been to incorporate sufficient robustness to ensure mechanical integrity. Biological materials often incorporate this function – the horns of many mammals are sheathed in fibrous keratin which is insensitive to notch weakness when damp. Desirable characteristics for mechanisms and deployables include adaptive materials (shape memory alloys) for vibration suppression, self-healing materials (ionomers), tactile surfaces (piezolelectric / magnetostrictive / electrostrictive materials), multifunctional structures with embedded molecular wires and optic fibres, structures which can alter their viscosity (electrorheological / magnetorheological fluids), etc.

Biomimetic Methods of Propulsion

Movement is a characteristic of the animal kingdom defined by the process of energy intake by feeding. Animals search for food while plants extract food from the environment directly. Movement is a necessary part of exploration and animal locomotion provides the basis for animal survival – the avoidance of threats and the acquisition of resources. The ability to move is the key to intelligence – animals which are mobile (by virtue of their heterotrophic energy assimilation) possess nervous systems, while plants which are static (by virtue of their autotrophic energy assimilation), do not. Molluscs are commonly sessile or slow-moving and have rudimentary nervous systems. Cephalopods, however, are highly mobile and are characterised by sophisticated nervous systems capable of supporting complex, problem-solving behaviours. Indeed, movement is a fundamental signature of life at microscopic scales. Movement is essentially the actuation component to a control system. In planetary exploration, biomimetic locomotion offers the potential for robust exploration in hostile environments with high scientific returns per platform per mission. We suggest that the key to biomimetic locomotion of all types is the approach to control – robust locomotion requires the implementation of central pattern generation, sensory feedback and preflexes enabled through structural compliance. Robotic control is mainly concerned with precise positional placement or the application of precise forces. Legged locomotion in animals relies heavily on the compliance of the body provided by the spine in the case of vertebrates. In invertebrates such as arthropods, this is provided by the joints between the three body segments as well as compliance in the jointed legs. We suggest that "smart" structures may contribute significantly to the implementation of force feedback and preflexive compliance – muscles provide actuation, damping and feedback. Most forms of biomimetic propulsion basically fall into 4 categories: legged walking/crawling, worm/snake, winged flight, and swimming.

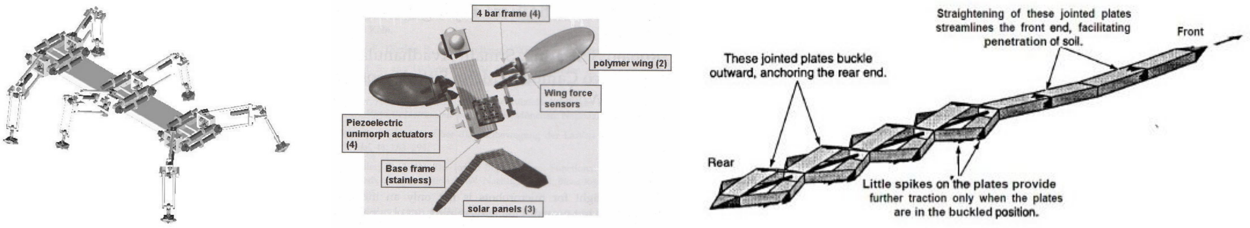

Fig. 1. a) Lava Robot b) UC Berkeley's RoboFly concept c) NASA/JSC worm robot proposal

Biomimetic Methods of Energy Generation & Storage

One of the most promising potential developments in biomimetics for space applications is artificial photosynthesis and the development of related redox reactions. Artificial photosynthesis offers a number of advantages over existing solar panel technology. Firstly, the efficiency might be much greater than traditional solar collection technologies. As it is based on a biochemical architecture that has evolved over 3.5 billion years, it is a much more refined method of gathering solar energy that is much more efficient per unit area than current solar panel technology. Secondly, it opens itself up to possible improvements.

Plants do not need to be 100% efficient at photosynthesis. Indeed, the highest efficiency in plants is around 1-2% [15]. They only need to be as efficient as is required to gather energy for their metabolic processes. Any higher efficiency does not provide greater competitiveness in the natural world. However, for applications in space, the more efficient the solar collection technology is, the less area it will take up and the more energy per unit area will be gathered, so there are good reasons to want to make photosynthesis more efficient. Directed alterations in the architecture of the photosynthetic structure could be used to make more efficient solar collectors and this is an area of emerging focus. Artificial photosynthesis could be used to provide power for a number of spacesystems including main power using systems (life support, scientific instrumentation etc.) and systems on the smaller scale such as nano-machines used to care of the exterior of spacecraft where sunlight impinging on the craft could be used as the source of energy.

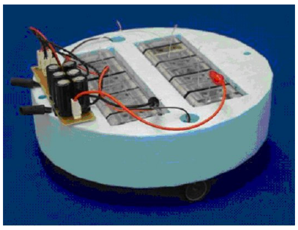

Fig. 2. EcoBot Fuel Cell Powered Micro Robot

Fuel cells are an established method of power generation using "cold combustion" of a fuel (typically hydrogen, methane or methanol); the oxidiser is usually oxygen, but other substances such as sodium ferricyanide solution are often used for the biological type. They can generate electricity without significant temperature rise in a similar method to batteries, avoiding the efficiency penalties of heat engines arising from the Laws of Thermodynamics – efficiencies of up to 80% are possible in practical applications. They were invented as long ago as 1843, but had little practical use until the Apollo space missions and continue in space-based use today through powering the Space Shuttle [Smithsonian Institution 2001]. Since they are non-polluting (their exhaust is water vapour, which can be harvested for astronauts to drink in spacecraft applications) and have the potential to generate large quantities of power they are also gaining in popularity for terrestrial products such as electric cars and mobile phones.

Immunological Approaches to Self-Defence

The immune system consists of a large number of cells of several types dispersed through the body that collaborate to protect an organism from a variety of threats, both external (disease-causing agents such as parasites, bacteria, viruses and toxins) and internal (mutant cells that might become cancerous), collectively termed “pathogens”. This function requires two stages: first, recognition of foreign substances that could cause harm (termed “non-self”, as opposed to the “self” substances that make up the organism), followed by their destruction. Computer programmes have been written that successfully use software analogues of the recognition mechanism for applications ranging from protecting computer systems from viruses to data mining, which are termed “artificial immune systems” or AISs. The threat destruction mechanism has not yet been imitated since more suitable alternative methods already exist.

The human immune system comprises an extremely complicated network of interacting cells and chemical messengers (hormones). It is able not only to produce a rapid generalised (“innate”) response to an invading pathogen but also to adapt specific counter-measures to combat it over a longer period of time. For the purposes of constructing artificial immune systems it has not proved necessary to mimic the human or any other immune system in every detail to achieve results; rather certain key principles have been abstracted from the lifecycle of a particular kind of immune system cell known as a B-lymphocyte or B-cell and applied to the computer realm [12].

Biological Behaviour Control & Navigation

The robotic system provides the most demanding test of AI techniques since it requires the intelligent control system to interact with the real world via a physical robot body. Sensory input and motor output are not analogues of the standard peripheral read and write commands in a computer programming language. The physical embodiment of the information processor (the body) provides a buffer to the external environment [6]. Dreyfus [4] suggested that bodies are a necessary pre-requisite for intelligence and that disembodied computing systems will never exhibit truly intelligent behaviour. The body provides a fundamental system of reference for cognition. All animals that are mobile require general-purpose perceptual and behavioural repertoires sufficient to deal with a variety of different environments in order to survive compared with animals (such as molluscs) that remain fixed and so are exposed to a limited repertoire of problems and conditions.

Behaviour depends on the environment in which the agent is embedded by virtue of evolution, e.g. foraging strategies for food require complex navigational skills. Control is concerned with the generation of desired behaviours in robotic agents – we consider control at different hierarchical levels. Indeed, control and navigation are fundamental to animal survival. Animal behaviour is adaptive in that it adjusts to the changing external environment. Simple animals like insects are capable of autonomously adapting a limited repertoire of basic behaviours to variations in the noisy complex environment of the real world. Animals possess limited motivations which determine their behaviour – hunger, libido and fear. Such motivations are combined with sensory data to generate dynamic goals and control perceptual attention. Hence, the environment does not produce a given behaviour, but merely triggers it. Complex behaviour is still a reflection of the complexity of the environment. Motivation for motor action usually resides in the physiological state of the agent often correlated with deprivation of a resource such as food. Insects are capable of adapting a limited behavioural suite to the uncertainties of the real world. Animal behaviour is adaptive in that it is continually adjusted to meet the changing internal and external conditions. Complex behaviour is generated by a series of sequential behaviours whereby the output of one behaviour triggers the next one.

Table 1. Levels of Behaviour [2]

Level	Module	Effect
Level 0	Collide, Runaway	remains stationary until a moving obstacle approaches it
Level 1	Wander Randomly Object Avoidance	generate new headings periodically Accepts force vector input from Level 0 and suppress output from Runaway module
Level 2	Explore	finds a corridor to a specified goal at a distance and moves towards it (likened to exploratory behaviour for the provision of information)
Level 3	Build Cognitive Maps	plan routes between landmarks
Level 4	Monitory Environment	monitors dynamic changes in the environment
Level 5	Identify Objects	identifies objects in environment and reasons about tasks to be performed on them
Level 6	Plan Tasks	formulates plans to change the state of the world as required
Level 7	Reason About Object Behaviour	reasons about object behaviour in the world and modifies plans accordingly

Memory – Beyond Behaviour Control

The CAM-brain (cellular automata machine) is a hardware-based electronic neural network of 38 million artificial neurons on 72 FPGA (field-programmable gate array). Each of 3276 modules of 1152 neurons is trained to perform a specific task using genetic algorithms to evolve connections within the module. Control genes are evolved to generate inter-module interconnections. A more simplified brain architecture may be represented in Fig. 3.

Mammals have two different types of memory that use two different brain structures for encoding information. The brainstem is associated with reflex behaviour and lower level learning. Memory traces in the human brain are localised to the cerebellum, hippocampus, amygdala and cerebral cortex. Working memory is associated with the prefrontal cortex, particularly the principle sulcus, which accesses relevant stored information in the cerebral cortex – working memory provides moment-to-moment awareness and retrieves archived information (similar to a "blackboard"). Long-term memory storage occurs in the cerebral cortex, which is also the region responsible for higher cognitive processes in mammals. The temporal lobes on the inner surface of the underside including the hippocampus are responsible for the storage of new long-term memories.

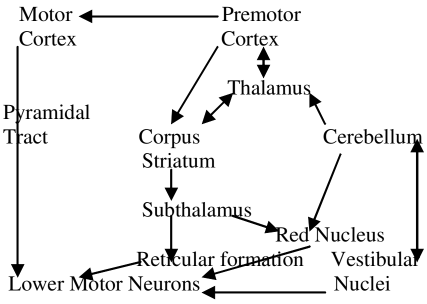

Fig. 3. Simplified Brain Architecture

Biological Learning

Simple animals (such as insects) behave through standard responses to stimuli. More complex vertebrates augment these responses with a world model that they use to select sensory information to plan courses of action to achieve their goals. The addition of learning provides the ability to adaptively use the world model to predict and compare predicted and actual outcomes of courses of action to update the knowledge structures for further use. The world model allows planning of future behaviours through simulation – simulation is reversible unlike action in the real world. Learning may thus be used to impart knowledge and skill to robot behaviours by accommodating the variability of the environment. Learning provides for greater complexities in behaviour beyond instinctive reflexivity. Learning is a much-desired capability and may be considered an indispensable component of intelligent behaviour [3]. A learning machine consists of a learning protocol specifying the way in which information is obtained and a deduction procedure which generates recognition algorithms for the learned concept in polynomial time [14]. The deduction procedure must in each case output a close approximation to the learned concepts such that it never outputs a positive when it should not but almost always outputs a positive when it should. Once learned, the concepts should be represented in memory in some way by being integrated into the original knowledge base. To acquire new knowledge efficiently, the system must already possess a degree of prior knowledge.

Genetic & Neural Approaches to Learning

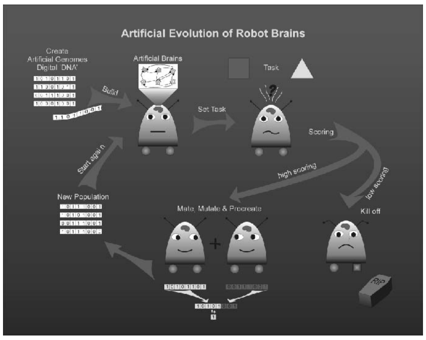

Fig. 4. An illustration of an evolutionary search algorithm applied to the problem of developing a robot control system.

Algorithms based on biological analogies have become commonly adopted for solving difficult problems: genetic algorithms [7] (and variants such as genetic programming [10] and evolution strategies [11] – collectively known as evolutionary algorithms) provide the basis for the evolutionary search of solutions to NP-hard problem spaces; neural networks (highly simplified idealisations of biological neural architectures) provide the basis for the generation of non-linear functions for robust pattern recognition and for control systems based on non-linear dynamics. Evolutionary algorithms are a range of machine learning mechanisms inspired by biological evolution. The genetic algorithm typically codifies solutions to the problem at hand as numeric strings, which can be thought of as artificial genotypes (bit strings were once the dominant representation, integer or real number encodings are now widely used). A population of these strings are subjected to a selection process whereby the best solutions are more likely to be chosen. A new population (the next generation) is created by applying various operators to the strings selected from the current population. The mapping between the strings and a solution to the problem can be straight forward (a simple list of values for variables) or complex (the definition of a 'developmental' process whereby the string is converted into a solution). Selection operates according to fitness function (or fitness metric), which measures the relative merits of competing solutions defined in the population. Over a series of evolving generations, increasingly fit solutions to the problem are generated. Genetic programming relies on a very similar scheme but adopts a high level language representation scheme (such as Lisp) that can be represented as tree structures. Genetic programming representations do not always utilise mutation, as it can be difficult to define suitable operators that do not result in illegal programs most of the time. The processes involved in an evolutionary algorithm are illustrated in Fig. 4. Here the problem is to evolve the control system for a robot; hence the fitness measure is related to the behaviour generated in a robot by a control system specified by an artificial genotype string.

Biomimetic Sensors & Signal Transduction

Sensors are a necessary component to any closed loop control system. They provide feedback data on the status of the environment. Animals are adaptable and robust, capable of learning sophisticated navigation strategies and are supported by a rich array of sensors [9]. In particular, biological organisms are characterised by distributed sensing capabilities which provide the basis for protection through reflex action. The basis for most biomimetic sensors is microtechnology, particularly for cantilevered sensors. For harsh environments, Si substrates are limited to 250°C so wide bandgap semiconductors such as SiC with a bandgap of 2.2 eV are more appropriate for high temperature operation on planets such as Mercury or Venus. SiC has a high elastic modulus (of 448), high Moh's hardness (of 9), high wear resistance (of 9.15) and chemical inertness to acids making it ideal for mechanical components. SiC does not melt but sublimes at 1800°C and can be grown as thin films by atmospheric or low pressure chemical vapour deposition on SiO_2 for SOI (silicon-on-insulator) fabrication. Hair-like mechanical sensors may be based on pressure sensing piezoelectric cantilevers – such sensors are ubiquitous in the biological world. The vestibular sense is evolutionarily the most ancient sensory modality that, in fish and crustaceans, is implemented by the statocyst where a chamber containing a massive particle (usually calcium); the chamber is lined with hair receptors that sense the position of the particle and so sense orientation. As an illustration, the animals can be confused if the calcium particle is replaced by a ferromagnetic one and the animal is placed in a controlled magnetic field! The function of hair cells in the human ear for both hearing and vestibular control are well-characterised.

High-Level Cognition by Symbol Manipulation

Autonomous control systems should be capable of performing well under significant uncertainties in both the system and the environment for extended periods of time without external interaction. The best way to achieve autonomy is to utilise high-level decision-making techniques, ie. intelligence to provide a predictive capability – intelligent control is the means to achieve autonomy in adaptive systems [1]. This allows the anticipation of the outcome of behaviour and allows goal-oriented actions to be implemented to achieve some purpose. This involves the process of internalisation of external reality to facilitate its simulation. Planning may be regarded as internalised motion which constructs the potential consequences of actions. The incorporation of intelligence at higher levels of the control system implies the need for flexible decision-making and reasoning. The ultimate goal of artificial intelligence (AI) research is to impart human level intelligence to computing machines.

Several properties are required of intelligent machines: they must be able to use partial and incomplete results, use due process empirical reasoning as well as logical deductive reasoning, be capable of self-reflection, and perform tasks efficiently. At a minimum, intelligence requires the ability to sense the environment, make decisions and produce actions to adjust to new situations and function reliably. In fact, this is precisely the definition of a control system. The ability to plan, which implies the ability to predict future events, forms part of this control system. Here we restrict ourselves to logic, reasoning and planning that form mainstream AI.

CONCLUSIONS

The information provided here is just a brief summary of the extensive work the team has put forth to collect information on the biologically inspired technologies and techniques that are being researched around the world. The team has begun focusing the collection of general biomimetics research into a more space-based compilation of bio-inspired enhancement to current space system technology. In the coming months, we will be looking more deeply into the existing biomimetics research for space application and eventually concentrating on those capabilities most beneficial for the design and development of three bio-inspired space missions: a 6-legged Mars walking explorer, a flying robot for Titan investigation, and a wood wasp-like digger for subsurface discovery into Europa's inner secrets.

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