

A Critical Review Paper on “Biomimetic Robotic Systems and Paradigms for Space Exploration”

Submission dated: 20th March 2007

Review paper prepared for Biorobotics class - ENGRMAE 250 (Winter 2007)

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I. Introduction

This review paper discusses the state of current and future research in the emerging field of biologically inspired robotic systems for space exploration. It presents the reader with a critical summary of papers which have made significant advances in applying biomimetic principles to solve current problems in planetary and deep space exploration missions. It then makes a critical comment on the current state of affairs in this field by considering the range of possibilities and constraints derived from learnings presented in the referenced papers.

II. Overview

Biomimetics is an already vast and growing area of research which covers a huge range of traditionally separate disciplines such as materials science and artificial intelligence and there are strong reasons why biomimetic engineering could have significant application to robotic space exploration. Firstly, space exploration involves alien environments that are harsh, and to a greater or lesser extent undefined beforehand, with a degree of dynamic variability that cannot be predicted and therefore explicitly accounted for in the design stage of a mission. So the need to incorporate some measure of reactivity is a critical requirement. Secondly, long communication delays and requirement for intense short-term activity during crucial mission phases entail the design of a system that is endowed with proactive goal-directed behavior, autonomy, adaptive intelligence and self-repair (qualities that are extremely hard to engineer in existing space vehicles by restricting design to traditional engineering principles). Thirdly, apart from alien terrestrial ground exploration, there has also been a growing interest in using robots to inspect and repair space vehicles as well as a need to reduce power consumption during long hours of unmanned operation. Both of these demand novel approaches to power consumption which is exclusively mentioned in the paper "*WaalBots for Space Applications*" which discusses the application of the dry adhesion attachment mechanism that allows lizards to rapidly and efficiently scale walls and hang from ceilings.

Considering the above demanding requirements of space exploration robotic vehicles, it is but natural that we turn to biological and natural systems that have found efficient solutions to many problems that engineers face. Characteristics that are common to biological systems include robustness, autonomy, adaptability, intelligence, energy efficiency and the ability for self-repair. However, what is more inspiring is that nature continually resolves these problems incrementally as conditions change. Thus, to be able to harness individual engineering concepts that come from nature has the potential to revolutionize the way future space systems are engineered.

Significant research is underway at NASA's Jet Propulsion Laboratory and by the Advanced Concepts Team at the European Space Agency into investigating the application of biomimetic engineering to future activity in space. Two excellent pointers to give the reader a headstart in this field are the papers "*Biomimetics Applied to Space Exploration*" and "*Biomimetics – A new approach for space system design*" which give an overview to the need of such an interdisciplinary application followed by a discussion on its current and future concentration areas. Building on this foundation, the paper introduces "*Bioinspired Engineering of Exploration Systems for NASA and DoD - From bees to BEES*" which discusses the BEES project whose intent is to distill the principles by which natural systems deftly accomplish several crucial functions such as autonomous navigation, hazard avoidance, altitude hold, visual search, and identification of features of interest for further imaging and study.

The next two papers i.e. “*Biomimicry as Applied to Space Robotics with Specific Reference to the Martian Environment*” and “*The Benefits and Applications of Bioinspired Flight Capabilities*” further elaborate on these functions specifically in the context of biomimetic robotic systems for Mars exploration. “*WaalBots for Space Applications*” as mentioned earlier is next reviewed followed by “*Methodical approach to implement biomimetic paradigms in the design of novel engineering and space systems*” which proposes the basis for a biomimetic design process that is generally applicable, comprehensive and systematic in the search for solutions.

Next the potential applications of micro technology which is thought to be enabling for biomimetics, allowing functionality at smaller scales, closer to those exhibited in many biological systems is discussed in the paper “*Potential Biomimetic Space Systems enabled by micro technology*”. “*Novel Approaches to Miniature Flight Platforms*” builds on this foundation of micro technology focusing on the high degree of innovation required to make practical miniaturized flying machines on the scale of small birds and insects. Finally, this review paper concludes with a philosophical statement on the fact that biological inspiration does not always lead to a viable and implementable design, so techniques not found in creation may need to be employed which is the central point of discussion of the paper “*Beyond biologically inspired insect flight*” as it tries to make a philosophical distinction between “Biomimetic” and “Biologically-Inspired” air vehicle design.

III. Critical Summaries

Biomimetics Applied to Space Exploration

Dr Mark Ayre

This paper though brief is an excellent introduction to the potential application of biomimetic engineering to space exploration. Since biomimetics has many application areas, the material does not exclusively adhere to a discussion on planetary robotics which is the primary review focus of this paper, but categorizes it into 4 domains that form the research interests of the Advanced Concepts Team at the European Space Agency and also the basis for further papers to be critically examined in the course of this critical review. It begins with a general introduction to biomimetics followed by an explanation of why its principles may be applicable in the arena of space exploration the most compelling being the fact that as space engineered systems become more and more complex, it is understandable that they should begin to exhibit characteristics of biological systems which are essentially an engineering response performed under the same physical constraints that engineers face.

The paper then details the individual application areas of “Autonomy and intelligence for spacecraft”, “Planetary and orbital robotics”, “Control and monitoring of life support systems and crew health” and “ISRU (In-Situ Resource Utilization) implementation”. Given the focus of this review paper, the planetary robotics section is of most interest since it mentions the BISMARC (Biologically Inspired System for Map-based Autonomous Rover Control) system, a hybrid neural network/behaviour based control system and the biomorphic explorers project (‘BEES’) that displays both form and control biomimicry. Another interesting example mentioned is the Entomoptor project that has the goal of developing a fully autonomous insect-analogue with crawling, swimming and flight capability. The paper concludes by briefing the current work within the Advanced Concepts Team and hints to possible future directions in each of the above areas.

However, given the possibilities of biomimetic space applications, the paper does not take a biased approach to touting biomimetics as the quintessential engineering paradigm but instead is fair enough to warn the reader as to why biomimetic solutions are not always going to be the best choice. It supports this statement with examples of engineering artifacts such as the wheel, jet or rocket engine which have allowed human-engineered systems to perform far beyond biological systems in many ways. Thus by the end of the paper the reader is left with an introduction to the field as well as knowledge of a fascinating array of possible biomimetic space applications but most importantly with an understanding that solutions to engineering questions should not always be allowed primacy because they are biomimetic and therefore ‘in vogue’, and that the practical satisfaction of the broad mission requirements and objectives should be the ultimate objective, not the construction of a biomimetic system just because it is pleasing to do so.

Biomimetics – A new approach for space system design

Carlo Menon, Mark Ayre, Alex Ellery

This paper is a more elaborate discussion of the key application areas presented in the previous paper. It presents the reader with a “Biomimetics Technology Tree” that succinctly categorizes the biomimetic research areas such as reflexive and rhythmic control, locomotion, fabrication, muscles, actuators, power generation, storage, learning mechanisms, novel structures, ecological mechanisms etc. which is a good reference for the design of an extremely complex system such as a biomimetic space robot given that it integrates results from each of these areas and that it has to feature the best of reverse engineered concepts from nature to autonomously adapt to an uncharted territory. An explicit mention of biologically inspired solutions for mobility in air, on ground and in liquids is made along with those for digging mechanisms which could be employed by a robot rover for subsurface sampling and various other mission scenarios. The Venus flytrap's energy storage structures are mentioned as being possible frameworks that could be employed in jointless deployable mechanisms. The paper concludes by stating that there are numerous instances of technology and mission requirements that range from bio-inspired artificial intelligence to onboard data-management systems, formation-flying control, deep-space navigation, rendezvous and docking, autonomous orbital etc.

Thus a reading of this paper leaves the reader with a more in-depth knowledge of the application areas and gives an understanding of the fact that a biomimetic robotic system for space will have to base its design principles on a myriad of reverse engineering concepts that we are only beginning to understand. The decoding of the human genome and its applicability to understanding biological life forms is a significant step forwards to building a reverse engineered space exploration robotic system that is robust, autonomous and adaptable. Although precise examples and experimental results have not been documented in the paper which could have greatly enhanced the understanding of current research work in this field, it only leaves the reader with an open mind to think of the possibilities.

Bioinspired Engineering of Exploration Systems for NASA and DoD - From bees to BEES

Sarita Thakoor, Javaan ChahI, M.V. Srinivasan, L.Young, F. Werblin, Butler Hine

This paper discusses the breakthrough bioinspired engineering of exploration systems (BEES) project for solving pressing NASA and DoD needs. It is a significant step forward in the area of biomimetics for space exploration since it adopts a strategy of distilling selected insect-inspired strategies with mammalian visual search, pattern recognition, and image understanding to obtain novel solutions for

navigation, hazard avoidance, altitude hold, stable flight, terrain following, and gentle deployment of payload which provides potential solutions for future autonomous robotic space and planetary explorers. Hence, the essential concept is to build explorer systems whose performance can surpass that of any particular organism, as they will possess a mix of the best nature-tested mechanisms for a particular function. After discussing the goal and concepts of the project, the paper dwells deeper into the technical nuances of incorporating the distillation strategy by explaining the honey bee based optic flow algorithms (for vision, hazard avoidance and navigation) which are based on motion vision found in insects rather than stereo vision. Thus, considering its distinct advantages over radar, ultrasound and lasers, optic flow is touted as the sensor of choice for terrain-following biomorphic flyers in Mars exploration.

Next the dragonfly-inspired biomorphic ocellus system is explained that would provide both altitude control, rate damping and stabilization to a pilot at lower cost in space, power, and mass. The idea behind the subsequent section on the autonomous recognition system inspired by mammalian retina function is that multiple features of the visual world are systematically parsed and processed in parallel and that these features are mapped to a stack of cellular strata within the retina. Each of these representations can be efficiently modeled in semiconductor cellular nonlinear network (CNN) chips. Finally, the paper describes a few future mission scenarios and deployment sequences for Mars exploration, uniquely enabled by these newly developed biomorphic flyers.

Thus, in the context of the overall paper, the BEES project is a promising step forward to advance the scientific principles for realization of efficient space explorer systems in terms of autonomous navigation and hazard avoidance. The paper does extremely well in restricting itself to this subset of biomimetic research which is an obvious advantage to a reader interested in exploring a particular research domain in this vast field even when specifically adapted to space exploration. Also since the BEES project is backed by funding from NASA and DoD, the authenticity of this paper's results and their future versions can be trusted.

Biomimicry as Applied to Space Robotics with Specific Reference to the Martian Environment
Gregory P. Scott, Alex Ellery

As one begins to think of the exciting new possibilities that arise from biomimetic space applications, one can't avoid thinking about our nearest planetary neighbor Mars and the desire to know a range of things about this planet. The NASA Mars Rover mission is our first step in this direction and the rover design can greatly benefit from what has been said and understood about biomimicry applied to space robotics. This paper is an effort in this direction with specific focus on investigating four different biomimetic locomotion systems: walking, flying, digging, and slithering as applied to robotic systems designed for exploring Mars. Its proximity to Earth, evidence that life might have existed billions of years ago and the many regions of terrestrial interest that the planet possesses make Mars of considerable geological, geochemical and geophysical interest. However, most importantly this environment proves to be quite diverse across the surface, requiring the ability to autonomously navigate around obstacles, without the benefit of human intervention or real-time control. We also understand that biological systems are hugely successful in solving problems encountered in their environments. Hence, it is but natural to apply the guidelines of biological systems to the engineering of spacecrafts and space robotics. On these lines, the paper presents biomimetic analogues to space robotics for e.g. the power system of an aircraft would be analogous to photosynthesis, ATP energy

storage in biological systems. In this section, a very interesting comment is also made on the fact that an ant cannot search for food and dig at the same time, but a spacecraft can charge its batteries through solar panels without involving other subsystems. However, the paper states that it is this inherent modularity that makes the system inefficient as a whole although it does not support this statement through a compelling explanation. It then presents a classification of biomimetic planetary explorers into Aerial and Surface-Subsurface systems with the *Entomopter* concept being the highlight of the former group which unlike conventional flapping-wing insects and animals, involves a front and rear fixed flapping wing that flap in opposing directions. The Robo-Beetle, Robo-Worms and Robo-Snakes are explored next that have been subsequently inspired from locomotion patterns in beetles, worms and snakes each of which possess its own inherent pros and cons to navigate their environments.

The paper concludes with a “still in progress” opinion on the state of biomimetic space research saying that scientists in this field are still in the process of evaluating the existing research in order to determine the most appropriate selections for application to space exploration. According to the paper, the most likely candidates that hold promise for a more detailed research are the cockroach inspired 6 legged walking robot (e.g. RHex) and the Entomopter with its large wingspan, light weight and simple design. Hence, overall the paper concludes by saying that whatever the final selection be as a specific baseline for biomimetics in space robotics, the advantages of a biologically inspired approach to robotics has numerous benefits over traditional space robotics and that increased autonomous control and learning behaviors are sure to increase the scientific rewards of a space mission.

The Benefits and Applications of Bioinspired Flight Capabilities

Sarita Thakoor, Nathalie Cabrol, Norman Lay, Javaan Chahl, Dean Soccol, Butler Hine

The BEES project currently underway under contracts from NASA and DoD (for robotic space exploration & reconnaissance and surveillance respectively) is perhaps the single most highlighted project pertaining to this field and has been exclusively referenced in many papers. This paper elaborates on the flight capability dimension of the project again exclusively in the domain of Mars exploration. It specifically addresses the challenges of flight on Mars, explains the scientific need for such flyers (the most important being that many sites on this planet require autonomous flyers that can cover hundreds of kilometers to acquire proper understanding of their history), highlights the (BEES) flyer development by giving actual design data and performance numbers from the project's first prototype and finally describes a few viable mission architecture options that allow reliable data return from the BEES flyers.

The need for the BEES project arises from the inherent difficulty of conventional flight over Mars due to its thin atmosphere, lack of magnetic compassing for navigation, and the limited telecommunications or navigational infrastructure. The goal of this project thus is to provide a close-up bird's eye view of the planetary terrain through design of biomorphic flyers incorporating the best of capabilities from three separate species: the dragonfly, honeybee and the rabbit. The project proposes to test its results by demonstrating a proof of concept simulation experiment at a terrestrial analog Martian site by emulating selected conditions of Mars. The demonstration will consist of launching/deploying a variety of BEES flyers each containing biologically inspired technologies capable of, for example, autonomous real time navigation, visual search, selective feature detection, intelligent flight control and image enhancement. Thus, the reader is left with an appreciation of the critical need for bioinspired flight capabilities for exploring the harsh environments of Mars and other planets.

WaalBots for Space Applications

Carlo Menon, Michael Murphy, Francesco Angrilli, Metin Sitti

Given a terrain such as Mars where a myriad of terrestrial features are present such as craters, gullies and canyons, a number of navigational strategies have to be incorporated in order for an autonomous robotic surface exploration to be successful. Simple rolling mechanisms can quickly find themselves in trouble and can be deleterious to the entire mission. The Robo-Beetle mentioned in paper 4 of this review emphasizes robust insect surface locomotion with manipulative capabilities, while the Robo-Worms and Robo-Snakes have been discussed in the context of robotic navigators capable of penetrating planetary surfaces. But what about climbing? It is perhaps nature's most important gift to certain animals and creatures for their survival. It is also a mechanism by which certain creatures like lizards can navigate circumferences and odd surfaces by certain adhesive forces. In an unknown planetary terrain, this feature could be the fine line between success and failure. For example building a robotic explorer that can collect samples from surfaces of craters at odd angles of inclination could result in more successful results when compared to having a simple surface roller which is trained to navigate relatively flat surfaces alone.

This breakthrough paper presents a revolutionary concept of incorporating the same dry adhesive forces that allow lizards to rapidly and efficiently scale walls or hang from ceilings into robotic explorers with an attachment mechanism that requires low power consumption. The paper begins by referencing gecko lizards whose ability to stick to surfaces lies in the very fine hairs on their toes which make contact with the surface to create a dry adhesion mechanism caused by Van der Waals forces that is independent of the nature of the surface and also accounts for an instantaneous speed of attachment and detachment. These are highly significant results when it comes to quickly navigating large unknown types of alien surface territories. The reader is then presented with the latest methods of fabricating biomimetic synthetic gecko fibres for use as dry adhesives followed by the design, analysis, construction and tests of climbing WaalBot prototypes. However the prototypes were equipped with conventional adhesives and focused more on emulating the actual gecko motion rather than validating the effectiveness of synthetic gecko fibres which is a drawback of this paper, although it concludes by saying that future work includes improving the synthetic hair fabrication procedure and the implementation of this material in robots for space operations.

Methodical approach to implement biomimetic paradigms in the design of novel engineering and space systems

Carlo Menon, Nicholas Lan

Although humans have been being inspired by nature for a long time, the application of biological principles has been on an ad-hoc basis which is detrimental to building a robust biomimetic system having characteristics such as adaptability, autonomy, miniaturization, holistic design, reliability, robustness, self-repair, self-replication. Hence, in the context of this review, the paper helps lay a solid foundation for a biomimetic design process that is generally applicable, comprehensive and systematic in the search for solutions. It takes a bottom-up approach to the design of such a methodology by specifying what is desired, identifying the challenges inherent in such an undertaking, and reviewing the state of previous work in this area. The difficulty of the whole endeavor though lies in the interdisciplinary nature of biomimetic research which integrates a number of disciplines that each have their own traditionally followed design processes and methods. Another key barrier is the translation of

designs from a biological to an engineering context wherein many solutions may be possible, incorporating different combinations of the principles and characteristics of the original system. The paper then talks about the current work in this area stating that various efforts have been made towards systematic transfer of ideas. For instance, databases have been developed for the matching of biological systems to potential engineering applications. It then builds upon this discussion by laying a set of guidelines to be followed for construction of the methodology and proceeds with its actual construction by defining a basic process flow in terms of inputs and outputs to the biomimetic system taking a problem-solution approach followed by decision making structures, implementation and testing. The methodology also exclusively defines the concepts of a function, characteristic, level of individual and system abstraction as they relate to a biomimetic system. All in all, the paper makes a fairly modest proposal for universalizing a methodical approach to implement biomimetic paradigms leaving open room for researchers to propose alternatives or iteratively modify portions of it. Actual results from systems implementing this methodology would have greatly helped in validating its effectiveness.

Potential Biomimetic Space Systems enabled by micro technology

Carlo Menon, Nicholas Lan

Till this point of review, we have considered technology to build biomorphic flyers and robotic surface explorers at a level of granularity that does not involve the micro-scale. But what if we want to navigate and penetrate extremely thin or narrow surfaces and holes or build reconnaissance and intelligent swarm systems that are practically invisible to the naked eye? The application of micro-technology is hence thought to be enabling for biomimetics since it will not only allow us to build systems that more closely resemble their biological counterparts in terms of size and functionality but will also lower the overall mass and volume that may provide great benefits to future missions. This is the precise point of discussion of this paper which highlights the work of The Advanced Concepts Team (ACT) of the European Space Agency (ESA) which has started working on projects for realizing the immediate the value of using MST to design bio-inspired space systems for future use. Among these projects are the Micro digging systems inspired by insects' ovipositor systems that exert forces needed for digging independently, such that additional reaction force is not required from the rest of the animal entailing low power consumption from their robotic counterparts. Possible applications of Micro digging systems include usage in micro-systems equipped with micro-sensors, micro-actuators capable of communicating through optical or radio links and as the main component of micro-moles for under-soil investigations. Similarly, other applications of MST such as micro strain sensors inspired by campaniform sensilla, distributed actuators and micro roots inspired from plant roots are appealing for further research. Overall, the paper is an excellent review on the fine prospects of utilizing micro technology for biomimetic space applications. Its discussion on MST is compelling when one considers the prospect of resultant systems consuming low development time, implementation and manufacturing costs, while enabling cumulative cost savings at mission level.

Novel Approaches to Miniature Flight Platforms

Robert Michelson

Flight is currently one of the most actively pursued research channels in the domain of biomimetic space applications. With the discussion of MST from the previous paper, it is only natural to consider the new possibilities that arise when one thinks about biologically inspired miniature flight platforms. However with hope and imagination comes a mix of challenges that is the focus of this paper as it

discusses the high degree of innovation required to make practical miniaturized flying machines on the scale of small birds and insects. The paper begins by giving a brief historical introduction of micro air vehicles (MAV) in the context of DARPA's vision of using them for reconnaissance and surveillance which is not really relevant when it comes to the discussion of biomimetic space applications but is a good review of why and how miniature flight models evolved. The most important discussion of this paper however is "Michelson's Aphoristic Decalogue of Flight Biomimetics" which is a list of ten universal principles that should always be considered when embarking upon the design of an efficient and affordable robotic flight vehicle that intends to leverage some aspects of a biological system. The paper then follows these guidelines with a design example of the Entomopter that adheres to them which is an excellent example of how to think "outside the box" to capitalize on biological systems yet not stopping at mere biomimicry but to go beyond to improve upon these natural systems. Overall, the paper does well at proposing the ten universal principles in the light of an efficient design example such as the Entomopter and which are alluring for any biomimetic flight designer to abide to.

Beyond biologically inspired insect flight

Robert Michelson, Messam Naqvi

The Entomopter as discussed in the above paper is an excellent example of design that goes far beyond simply biomimicry which is the primary focus of discussion of this paper as it seeks to distinguish between "biomimetic" and "biologically-inspired" air vehicle designs with the latter term being more native to the design principles of the Entomopter. The paper begins by discussing the key problems of current biomimetic flight machines which almost universally restrict their motion to kinematically correct flapping that does not precisely replicate the mechanisms used by insects and birds. This essentially is a reference to the fact that rudimentary mimicry of basic flying mechanisms have not led to efficient solutions that can be implemented in the context of a highly demanding robotic space mission. In the light of the ten universal principles discussed above, the paper then puts natural flying systems in context to critically analyze behavior and characteristics that can be employed to the modelling of small flapping wing aerodynamics. The conclusions of this paper are very much similar to the previous one. However the distinction between the two is that this paper takes a more philosophical approach to convincing the reader as to why biomimetic aerial systems can be modelled more efficiently if they are biologically-inspired rather than simply mimicked from nature.

IV. Critical Comment

From all the discussion that has been so far presented, it comes to one's understanding that biomimetics holds an array of novel possibilities and solutions for designing robotic space systems that can outperform the present ones on several factors such as autonomy, robustness, adaptive intelligence, self-repair, power consumption etc. These factors become even more critical in space exploration as the environments to be explored are typically harsh and unknown with dynamics and variability that cannot be completely accounted for [Reference: Paper 1]. Hence, there is an acute need for robotic systems that are biologically-inspired and not merely mimicked [Reference: Papers 9 and 10] to possess the above characteristics to explore uncharted terrains such as those on Mars. The most prominently backed effort in this direction is the NASA and DoD sponsored BEES project [Reference: Paper 3, 5] that adopts a strategy of distilling selected insect-inspired strategies with mammalian visual search, pattern recognition, and image understanding to obtain novel solutions for navigation, hazard avoidance, altitude hold, stable flight etc.

The Advanced Concepts Team (ACT) of the European Space Agency [Reference: Paper 1, 2] is another important division working towards key application areas of autonomy, intelligence, planetary and orbital robotics. Considering the focus of this review paper, current biomimetic planetary explorers can be classified into Aerial and Surface-Subsurface systems [Reference: Paper 4] with the Entomopter being the most prominent highlight of the former category while the Robo-Beetle, Robo-Worms, Robo-Snakes and Waalbots [Reference: Paper 6] being excellent research prototypes that can contribute to the construction of much superior surface explorers.

Micro-technology [Reference: Paper 8] is a key enabler for future miniaturized biomimetic robots given the need to not only closely resemble their biological counterparts in terms of size and functionality but also to lower the overall mass and volume that may provide great benefits to future missions. However even as we talk about such fantastic possibilities in this emerging field, there is a critical need to standardize a design paradigm that can be universally applicable across the various disciplines that make up biomimetics since robotic space missions are inherently complex involving a high degree of modularity and without standardization we cannot truly replicate the characteristics or behavior of a biological life form [Ref: Paper 7]. Also the design paradigm has to base itself on a philosophical distinction between “biomimicry” and “biological-inspired” robotic systems that we are to create [Ref: Paper 10].

As a line to conclude, biomimetics for space robotics holds never before experienced possibilities and is backed by some promising research exclusively devoted to the field. However, time can only tell if we are able to truly translate nature's simplicity or is simplicity itself impossible to replicate.