NATURE-INSPIRED DESIGN AND ENGINEERING (NIDE): A NEW TOOL FOR THE NEXT GENERATION OF ROBOTIC AND HUMAN SPACE MISSIONS

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The next generation of robotic and human space missions is getting more complex and complicated in their goals and objectives, they are of much longer time duration and they are going farther into the Solar System. These new space missions require a re-examination of the existing and traditional techniques and approaches that we have developed in the past and look to new approaches for developing and implementing the next generation of robotic and human space missions. The objective of the paper is to identify some key terms and concepts in the area of nature-inspired design and engineering and to provide a brief introduction/tutorial on nature-inspired design and engineering and its relevance to planning and developing the next generation of robotic and human space missions. Nature-inspired design and engineering may impact the following space mission engineering disciplines: atmospheric flight, structures, materials, guidance, navigation, control, remote sensing techniques and strategies, aerial and space recognition, artificial intelligence, decision making, communication, surface and sub-surface locomotion, energy collection and robotic manipulators.

Keywords: Nature-inspired design and engineering, biomimicry, biomimetics, robotic and human space missions, Solar System missions

1. INTRODUCTION

The next generation of robotic and human space missions is getting more complex and complicated in their goals and objectives, they are of much longer time duration and they are going farther into the Solar System. We are studying robotic missions to return to Earth collected samples from the surface of the Moon, Mars, asteroids and comets [1]. We are planning robotic missions to explore the intriguing moons of Jupiter and Saturn and to explore bodies at the very edge of the Solar System [1]. We are planning human missions to an asteroid [2] and Mars [3, 4]. These new space missions require a re-examination of the existing and traditional techniques and approaches that we have developed in the past and look to new approaches for developing and implementing the next generation of robotic and human space missions.

Can nature-inspired design and engineering (NIDE) be used to assist scientists, engineers, technologists, mission architects and project managers in the development of new robotic and human space missions? The objective of the paper is to identify some key terms and concepts in the area of nature-inspired design and engineering and to provide a brief introduction/tutorial on nature-inspired design and engineering and its relevance to planning and developing the next generation of robotic and human space missions.

Biomimicry or biomimetics is the examination of nature, its models, systems, processes, and elements to emulate, mimic or take inspiration from nature in order to solve human problems. The terms biomimicry and biomimetics come from the Greek words bios, meaning life, and mimesis, meaning to mimic or take inspiration from nature in order to solve human problems. Other terms often used are bionics, bio-inspiration, and biognosis [5]. In this paper, the terms bio-inspired and nature-inspired design and engineering will refer to solving problems or developing technology that emulates or takes inspiration from nature.

Natural or nature inspired design and engineering should be considered as potential engineering/technology solutions in the development of the next generation of robotic and human space missions. Unfortunately, the bulk of the current engineers, scientists and technologists working in developing space missions have really not been exposed to NIDE during their formal training. Despite demonstrated advantages, to-date relatively few NIDE solutions have been incorporated into space missions. However, this situation may be changing. Over the last decade, many of the countries top engineering universities have developed departments and programs in nature-inspired design and engineering, e.g., The Center for Bioinspired Engineering at the California Institute of Technology, the Wyss Institute for Biologically Inspired Engineering at Harvard University, the Center for Biologically Inspired Design at the Georgia Institute of Technology and the Department of Biological Engineering at the Massachusetts Institute of Technology.

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Natural systems, including biological systems, display many of the characteristics in the following list sought by engineers for safe and reliable robotic and manned spaceflight systems:

1. Highly autonomous, even intelligent
2. Highly integrated
3. Cooperative operation
4. Low weight
5. Low power consumption
6. Fault tolerance
7. Rapid adaptation to survival stressors
8. Self-assembling, self-replicating, etc.

For over 3.6 billion years since life originated and evolved on our planet, nature has been developing systems/subsystems that have direct applications to space missions. Some of these systems in nature include atmospheric flight, navigation, control, pattern recognition, communication, etc. For example, the approach to exploring planetary surfaces involves three distinct processes: flying through an atmosphere, landing on a planetary surface and exploring the planetary surface and atmosphere. In nature, for example, birds efficiently achieve these objectives of flying, landing and exploring. The characteristics of birds in landing and exploring the surfaces of the planets formed the basis of a detailed engineering study conducted by the European Space Agency [6]. An often-quoted example of nature-inspired design and engineering is the development of the first successful drone, the Albatross, developed by copying the flight characteristics of the bird by the same name.

Nature-inspired design and engineering examples have the potential to provide new insights and ideas that may impact several engineering and technology disciplines, including:

1. Atmospheric flight
2. Structures
3. Materials
4. Guidance
5. Navigation
6. Control
7. Remote sensing techniques
8. Remote sensing strategies
9. Aerial and space recognition
10. Artificial intelligence
11. Decision making
12. Data storage
13. Communications
14. Surface and subsurface locomotion
16. Robotic manipulators, activators and muscles.

Some examples of natural or nature-inspired design and engineering technology developments are described in an essay entitled, The 15 Coolest Cases of Biomimicry [7] and include:

- Velcro
- Passive cooling
- Gecko tape
- Whale power wind turbine
- Lotus effect hydrophobia
- Self-healing plastics
- The golden streamlining principle
- Artificial photosynthesis
- Bionic car
- Morphing aircraft wings

2. MORPHING AIRPLANES:
AN EXAMPLE FROM THE BIRDS

The discipline of atmospheric flight has been a leader in the application of bio-inspired design and engineering with the development of morphing airplane technology [8, 9, 10]. Morphing aircraft are multi-role aircraft that change their external shape substantially to adapt to a changing mission environment during flight. This creates superior system capabilities not possible without morphing shape changes. The objective of morphing activities is to develop high performance aircraft with wings designed to change shape and performance substantially during flight to create multiple-regime, aerodynamically-efficient, shape-changing aircraft [8]. The morphing aircraft concept continues today as part of NASA’s Breakthrough Vehicle Technologies Project. The goal of the NASA Morphing Project is to develop component technologies that enable aerodynamic surface shape change and that can be integrated into efficient air vehicles to provide a wide range of capabilities [8].

Some examples of NIDE that may be ripe for application to robotic and human space missions are identified below:

2.1 “Swarming” Search Strategy and Planetary Exploration.

The exploration of Mars and other planets using a fleet of small aerial platforms based on the principles of bio-inspired engineering of exploration systems (BEES) has been discussed in a series of papers [11-16]. The BEES concept is based on combining biological features and capabilities derived from three different biological species: the dragonfly, the honeybee and the rabbit. In the BEES concept, the flight control and navigation systems were inspired by the structure and function of the visual system and brain of insects [12-14]. The dragonfly uses remarkably simple optical mechanisms for flight speed determination that is based on non-directional texture detection, and allows for a simple feedback loop for controlling smooth landings on the surface. On Earth, bees, crickets and ants use sky polarization patterns in the ultraviolet/blue part of the spectrum as a direction reference to the position of the Sun. Such a mechanism wouldn’t have been independently evolved in animals if it weren’t an elegant solution to the migratory navigation problem.

Another example of insect behavior that may be relevant to planetary exploration is the swarming strategy of explorer bees. Once a hive reaches a critical size, explorer bees begin to search for an appropriate location for a new hive using a “swarming” strategy. The honeybee swarming strategy to find a location for a new hive may have relevant applications for planetary exploration, e.g., the search for caves on Mars [17].

2.2 A Bio-Inspired Design for Efficient Solar Energy Collection for Robotic and Human Missions

During the process of photosynthesis, solar energy is utilized
to convert carbon dioxide and water vapor to oxygen and carbohydrates. Carbohydrates are a source of nourishment for the entire planet. Oxygen is required for maintaining life on our planet. It has been estimated that worldwide, the daily rate of solar energy absorption by vegetation is six times greater than the output of all the world’s power plants [18, 19].

A research group at the California Institute of Technology [18, 19] is designing an artificial leaf, which mimics the energy conversion process of vegetation. This “leaf” consists of a grid of silicon nanowires, each 1,000 times thinner than a hair. Each fiber is coated with a chemical catalyst. When exposed to the sun, a two-step process occurs. First, electricity is produced, as in solar panels. In the second step, the current of electrons splits water molecules into the component atoms of oxygen and hydrogen. The hydrogen and oxygen are then concentrated and stored.


In Australia, the compass termites build castles in the shape of huge flat chisel blades, always with their long axis pointing north and south. Such a shape exposes the minimum possible area to the strong midday sun but captures the maximum of the weaker rays in the early morning and evening when, especially in the cold season, the termites are grateful for warmth [21].

The termites Amitermes meridionalis and Amitermes laurensis construct remarkable meridional or “magnetic” mounds in northern Australia. These mounds vary geographically in mean orientation in a manner that suggests such variation is an adaptive response to local environmental conditions. Theoretical modeling of solar irradiance and mound rotation experiments show that maintenance of an eastern face temperature plateau during the dry season is the most likely physical basis for the mound orientation response. Subsequent heat transfer analysis shows that habitat wind speed and shading conditions also affect face temperature gradients such as the rate of eastern face temperature change. It is then demonstrated that the geographic variation in mean mound orientation follows the geographic variation in long-term wind speed and shading conditions across northern Australia such that an eastern face temperature plateau is maintained in all locations [22].

2.4 Reduction in Water Friction (Shark Dermal Denticles) for Robotic Transportation in Planetary Bodies of Water, e.g., Europa, the Water-Covered Satellite of Jupiter [23]

Sharks have a complex dermal corset made of flexible collagenous fibers and arranged as a helical network surrounding their body. This works as an outer skeleton, providing attachment for their swimming muscles and thus saving energy. Their dermal teeth give them hydrodynamic advantages as they reduce turbulence in the water when swimming.

2.5 Bio-Inspired Design and Engineering for Robotic Manipulators, Activators and Muscles

A series of recent papers have considered bio-inspired design and engineering in the development of robotic manipulators, activators and muscles [24-29].

3. SOME STUDIES OF BIO-INSPIRED DESIGN AND ENGINEERING RELEVANT TO SPACE EXPLORATION

To-date, the application of bio-inspired design and engineering to robotic and human space missions has been the subject of relatively few papers/reports. Examples of such papers/reports are: Future Robotic Exploration Using Honeybee Search Strategy: Search for Caves on Mars [17], Biomimicry As Applied to Space Robotics with Specific Reference to the Martian Environment [30] and A Biologically Inspired Rolling Robot for Planetary Surface Exploration [31]. Hopefully, the scarcity of these studies and papers will increase in the future as scientists, engineers and technologists learn more about nature-inspired design and engineering and its potential applications to the next generation of robotic and human space missions.

4. CONCLUSIONS

In conclusion, in the 3.8 billion years of the evolution of life on our planet, nature has solved problems of great complexity in various species. However, NIIDE methods have not yet been utilized by spacecraft and mission designers, engineers, scientists and project managers designing and developing future NASA space missions. A major opportunity exists to incorporate NIIDE approaches and techniques into the development of robotic missions to the planets, their moons, asteroids and comets, as well as in human missions to asteroids and Mars. NIIDE may be valuable approach due to the complexity, challenges, long-duration and great distances of the next generation of robotic and human missions.

It seems appropriate to conclude this article with a 500-year old quote from Leonardo da Vinci:

“Those who are inspired by a model other than nature, a mistress above all masters, are laboring in vain” [32].

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