Biologically Inspired Technology using Electroactive Polymers (EAP)

Yoseph Bar-Cohen,
Jet Propulsion Lab, California Institute of Technology
4800 Oak Grove Drive, Pasadena, CA 91109-8099,
yosi@jpl.nasa.gov, web: http://ndeaa.jpl.nasa.gov

ABSTRACT

Evolution allowed nature to introduce highly effective biological mechanisms that are incredible inspiration for innovation. Humans have always made efforts to imitate nature's inventions and we are increasingly making advances that it becomes significantly easier to imitate, copy, and adapt biological methods, processes and systems. This brought us to the ability to create technology that is far beyond the simple mimicking of nature. Having better tools to understand and to implement nature's principles we are now equipped like never before to be inspired by nature and to employ our tools in far superior ways. Effectively, by bio-inspiration we can have a better view and value of nature capability while studying its models to learn what can be extracted, copied or adapted. Using electroactive polymers (EAP) as artificial muscles is adding an important element to the development of biologically inspired technologies. This paper reviews the various aspects of the field of biomimetics and the role that EAP plays and the field outlook n.

Keywords: Biomimetics, biologically inspired technologies, robotics, EAP, electroactive polymers

1. INTRODUCTION

The term Biomimetics [Schmitt, 1969] represents the studies and imitation of nature's methods, designs and processes. Through evolution, nature has "experimented" with various solutions to its challenges and has improved the successful ones. Specifically, nature, or biology, experimented with the principles of physics, chemistry, mechanics, materials science, mobility, control, sensors, and many other fields that we recognize as science and engineering. The process has also involved scaling from nano and macro to the macro and mega. Living systems archive the evolved and accumulated information by coding it into the species' genes and passing the information from generation to generation through self-replication. Surviving organisms that nature created are not necessarily optimal for the organism performance since all they need to do is to survive long enough to reproduce. Nature inventions are far superior in many areas over human made capabilities and adapting many of its features and characteristics can significant improve our technology [Bar-Cohen, 2005; and Vincent, 2001].

The specifications of Nature's designs consist of general features rather than making exact duplicates, where Nature's products are able to perform quite well while having an identity that distinguishes the individual members from each other in the same species. In contrast, when producing our commercial products at most efforts are made to duplicate the specifications of the same products as closely as possible to assure their quality and performance. The cell-based structure, which makes up the majority of biological creatures, offers the ability to grow with fault-tolerance and self repair, while doing all of the things that are the characteristics of biological systems. Humans have learned a lot from nature and the results helped surviving generations and continue to secure a sustainable future. Adapting biology can involve copying the complete appearance and function of specific creatures as in toy stores where they are increasingly becoming filled with simplistic imitations in the form of electro-mechanized toys such as dogs that walk and bark as well as many others. Flying was inspired by birds using human developed capabilities, whereas the design and function of fins, which divers use, was copied from the legs of water creatures like the seal. Once human flying became feasible, improvements in aircraft technology led to capabilities that far exceed any creature that lives on earth.

Mimicking nature is effective not only in making useful devices and mechanisms. Biologically inspired terms help greatly in providing user friendly description of concepts and technical terms. For example, it is very clear which is a *male* or *female* connector, and also what does it means *teeth* of a saw. The use of the terms *intelligent* or *smart* suggests the emulation of biological capabilities with a certain degree of feedback and decision making. In the world of computers and software many biological terms are commonly used to describe aspects of technology including *virus*, *worm*, *infection*, *quarantine*, *replicate*, and *hibernate* to name just a few.

Structures are also widely copied; for example the honeycomb. While used for its efficient packing structure by bees (which is different than the use for low weight high strength in aerospace), the honeycomb has the same overall shape in both the biological and the aerospace structures. One may argue that the honeycomb structures, which are used in many of the aircraft structures of today's airplanes, were not copied from the bees [Gordon, 1976]. However, since it is a commonly known structure which was invented by nature many years before humans arrived, no patent can be granted in the "patent court" of nature to the first human who produced this configuration. Generally, biological materials [Carlson et al., 2005] have capabilities that surpass human made ones and these include the silk, leather and wool that are widely used to make clothing.

Plants also offer a model for imitation and they have evolved in various ways with some that produced uncommon solutions to their special needs [Stahlberg and Taya, 2005]. Besides their familiar characteristics, some plants exhibit actuation capabilities that we would expect from biological creatures. Such plants include the mimosa and the Sensitive Fern that bend their leaf when touched. The sunflower tracks the sun's direction throughout the day to maximize exposure to its light. Understanding the mechanism that drives this capability as locally controlled actuators offers potentially effective new motors.

2. BIOLOGY AS A MODEL

Nature consists of an enormous pool of inventions that passed the harsh tests of practicality and durability in changing environment. Effectively applying nature's inventions involves turning them into engineering capabilities, tools, and mechanisms and it would be helpful to sort biological capabilities along technological categories to inspire new mechanisms, devices and robots. Examples may include the woodpecker's ability to impact wood while suppressing the effect from damaging its brain. Another example is the ability of numerous creatures to operate with multiple mobility options including flying, digging, swimming, walking, hopping, running, climbing, crawling. Increasingly, biologically inspired capabilities are becoming practical including collision avoidance using whiskers or sonar, controlled camouflage, and materials self-healing. One of the challenging capabilities will be to create miniature devices that can fly with enormous maneuver capability like a dragonfly; adhere to smooth and rough walls like a gecko; adapt the texture, patterns, and shape of the surrounding environment like a chameleon, or also reconfigure its body to travel thru very narrow tubes like an octopus; process complex 3D images in real time; recycle mobility power for highly efficient operation and locomotion; self-replicate; self-grow using resources from the surrounding terrain; chemically generate and store energy; and many other capabilities for which biology offers a model for science and engineering inspiration. While many aspects of biology are still beyond our understanding or capability, significant progress has been made.

2.1 Materials and processes in biology

The body is a chemical laboratory that processes chemicals acquired from nature and turning them to energy, construction materials, various multifunctional structures and waste [Mann, 1995]. Natural materials have been well recognized by humans as sources of food, clothing, comfort, and many others where, to name few, one can include fur, leather, honey, wax, milk and silk [Carlson et al., 2005]. Even though some of the creatures and insects that produce materials are relatively small, they can produce quantities of materials that are sufficient to meet human consumption on a scale of mass production (e.g., honey, silk and wool). The use of natural materials can be traced back thousands of years. Silk, which is produced to protect the cocoon of the silkmoth, has great properties that include beauty, strength and durability. These advantages are well recognized by humans and the need to make them in any desired quantity led to the production of artificial versions and imitations. Some of the fascinating capabilities of natural materials include self-healing, self replication, reconfigurability, chemical balance, and multifunctionality. Many human-made materials are processed by heating and pressurizing, and it is in contrast to nature which always uses ambient conditions. The fabrication of biologically derived materials produces minimum waste and no pollution, where the result is biodegradable and is recycled by nature. Learning how to process such materials can make our material choices greater and improve our ability to create recyclable materials that can better protect the environment.

One of biology's best "manufacturing engineers" with an incredibly effective material-fabrication capability is the spider. It fabricates the web (Figure 1) to make a very strong, insoluble, continuous lightweight fiber and the produced web is resistant to rain, wind and sunlight. It is made of very fine fibers that are barely visible allowing it to serve its function as an insect trap. The web can carry significant amount of water droplets from fog, dew or rain. The spider generates its fiber while hanging on to it as it emerges cured and flawless from its body at room temperature and at atmospheric pressure. The spider has sufficient supply of raw materials for its silk to span great distances. The silk that is produced by the spider is far superior in toughness and elasticity to Kevlar, which is widely used as one of the leading materials in bullet proof vests, aerospace structures and other applications where there is a need for strong lightweight fibers. Though it is produced in water, and at room temperature and pressure, the spider's silk is much stronger than steel.

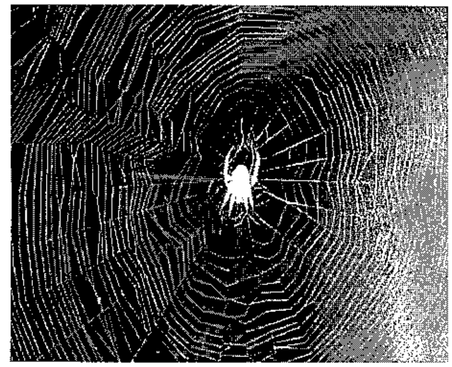

FIGURE 1: The spider constructs an amazing web that is made of silk material that for a given weight it is 5 times stronger that steel.

2.2 Robotics emulating biology

The introduction of the wheel has been one of the most important human inventions - allowing humans to traverse great distances and perform tasks that would have been otherwise impossible within the life time of a single human being. While wheel-locomotion mechanisms allows reaching great distances and speeds, wheeled vehicles are subjected to great limitations with regards to traversing complex terrain that have obstacles. In contrast, legged creatures can perform numerous functions that are far beyond the capability of an automobile. Producing legged-robots is increasingly becoming an objective for robotic developers and considerations of using such robots for space applications are currently underway. The entertainment and toy industries greatly benefited from advancement in this technology. Legged robots are even being developed for future NASA missions and an example of such a robot is shown in Figure 2.

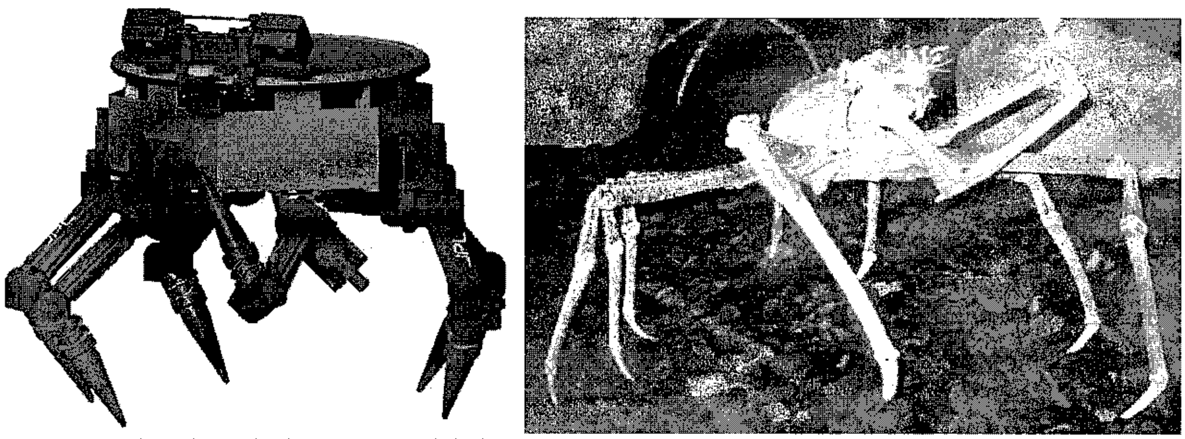

FIGURE 2: The 6-legged robot, LEMUR (Limbed Excursion Mobile Utility Robot), which is developed that the Jet Propulsion Laboratory [Courtesy of Brett Kennedy, JPL] and the crab in an aquarium.

3. ARTIFICIAL MUSCLES

Polymers that can be stimulated to change shape and size have been known for years. The functional similarity of such polymers led to their being named artificial muscles. Mechanisms of activation that make polymers respond with mechanical change include electric, chemical, pneumatic, optical, and magnetic. Electrical excitation is one of the most attractive stimulators that can produce elastic deformation in polymers. The convenience and practicality of electrical stimulation, as well as the recent years improvement of their capabilities, made the electroactive polymers (EAP) one of the most attractive among the activatable polymers [Bar-Cohen 2004, and Bar-Cohen 2005].

Generally, EAP materials can be divided into two major categories based on their activation mechanism: electronic and ionic. Most electronic polymers (electrostrictive, electrostatic, piezoelectric, and ferroelectric) require high activation fields (>150 V/μm) close to the breakdown level. However, they can be made to hold the induced displacement under activation of a DC voltage, allowing them to be considered for robotic applications. These materials have a faster response, a greater mechanical energy density, and they can be operated in air. In contrast, ionic EAP materials (gels, IPMC, conductive polymers, and carbon nanotubes) require drive voltages as low as 1–5 V and produce significant bending. However, bending actuators have relatively limited applications for mechanically demanding tasks due to the low force or torque that can be induced. Also, with some exceptions, these materials require maintaining their wetness and when containing water they suffer electrolysis with irreversible effects when they are subjected to voltages above 1.23-V. Except for conductive polymers, it is difficult to sustain DC-induced displacements.

Unfortunately, EAP-based actuators, are still exhibiting low force below their efficiency limits, are not robust, and are not available as commercial materials for practical application considerations. Each of the known materials requires adequate attention to the associated unique properties and constraints. In order to be able to take these materials from the development phase to use as effective actuators, there is a need to have an established EAP infrastructure. Effectively addressing the requirements of the infrastructure involves developing its science and engineering basis; namely having an adequate understanding of EAP materials' behavior, as well as developing processing and characterization techniques. Enhancement of the actuation force requires understanding the basic principles, computational chemistry models, comprehensive material science, electromechanical analysis and improved material processing techniques. Efforts are made to gain a better understanding of the parameters that control the EAP electro-activation force and deformation.

In 1999, the author challenged the world's research and engineering community to develop a robotic arm that is actuated by artificial muscles to win a wrestling match against a human opponent. The objectives for this challenge are to promote advances towards making EAP actuators that are superior to the performance of human muscles. Also, it is sought to increase the worldwide visibility and recognition of EAP materials; attract interest among potential sponsors and users; and lead to general public awareness since it is hoped that they will be the end users and beneficiaries in many areas including medical, commercial, and military. The first arm-wrestling competition with human was held against a 17-year girl on March 7, 2005 and the girl won against three robotic arms that participated. One of the competing arms and the human opponent are shown in Figure 3. Even though the arms did not beat the challenge, one of the arms was able to hold against the girl for 26-seconds and this is an important milestone.

FIGURE 3: An EAP driven arm made by students from Virginia Tech and the human opponent, 17-year old student

4. INTERFACING BIOLOGY AND MACHINES

Interfacing between human or animals and machine to complement or substitute our biological senses can enable important means for medical applications. Of notable significance is the interfacing of machines and the human brain. A development by scientists at Duke University [Wessberg et al., 2000 and Mussa-Ivaldi, 2000] enabled this possibility where electrodes were connected to the brain of a monkey and, using brain signals, the monkey operated a robotic arm, both locally and remotely via the Internet. This research is also being conducted at Caltech, MIT, Brown University and others research institutes. Progress in the past couple of years led to the development of chips that can recognize brain signals for movement and convert them into action [Musallam, et al, 2004]. Monkeys fitted with such chips were trained to move cursors on computer monitors, where such devices translate signals from the brain's motor cortex, the region that directs physical movement. Advances in this field have reached the level that recently, the US Food and Drug Administration (FDA) approved, on a limited basis, the conduction of such experiments on humans. For this purpose, Cyberkinetics, in Foxborough, Massachusetts [Serruya, et al, 2002] is developing this capability using microchips that are implanted in the motor cortex region of five quadriplegic patients to allow them mouse control and computer access. The near term objective of this study is to develop neural-controlled prosthetics. Using such a capability to control prosthetics would require feedback in order to provide the human operator a "feel" of the environment around artificial limbs. Besides feedback, sensors will be needed to allow users to protect the prosthetics from potential damage (heat, pressure, impact, etc.), just as the capability of our biological limbs. Currently underway there is a DARPA program entitled "Revolutionizing Prosthetics" that funds the development of a smart prosthetic hand that can operate and feel as good as a real human being hand taking advantage of the neurologists development in brain interfacing [http://www.darpa.mil/dso/solicitations/prosthesisPIP.htm].

Interfacing of vision and hearing devices and the human brain have also emerged where hearing devices are increasingly implanted and vision devices are currently at advanced research stages [Szema et al., 2005; and Agrawal et al., 2005]. Emulating the eye focusing mechanism as well as the iris and the eyelid are found in today's cameras. While significant advances were already made, the human eyes combined with the brain have far superior capabilities including image interpretation and recognition, ability to rapidly focus without moving the lens location in the eye, 3-D capability, high sensitivity, and operability in a wide range of light intensities from very dark to quite bright light. The need for such a capability has grown significantly with the emergence of small digital cameras that are now part of many cellular phones and webcams for telecommunication via computers. It is highly desirable to see via such cameras real-time images with the performance that approaches the human eye. Also, researchers are working to create implants that can help the vision-impaired regain the ability to see [Agrawal et al., 2005]. Increasingly, sophisticated visualization and image recognition are being used in security systems. One of the benefits of this capability, once the reliability issues are overcome, would be a standard operation as part of homeland security in airports, public areas or even in our homes.

5. CONCLUSIONS

After billions of years of evolution, nature developed inventions that work, which are appropriate for the intended tasks and that last. The evolution of nature led to the introduction of highly effective biological mechanisms, whereas failed solutions often led to the extinction of the specific species. In its evolution, nature archived its solutions in genes of creatures that make up the terrestrial life around us. Imitating nature's mechanisms offers enormous potentials for the improvement of our life and the tools we use. Humans have always made efforts to imitate nature and we are increasingly reaching levels of advancement where it becomes significantly easier to mimic biological methods, processes and systems.

Benefits from the study of biomimetics can be seen in many applications, including stronger fiber, multifunctional materials, improved drugs, superior robots, and many others. Nature offers a model for our efforts to improve our capabilities and address our needs. We can learn manufacturing techniques from animals and plants such as the use of sunlight and simple compounds to produce with no prolusion, biodegradable fibers, ceramics, plastics, and various chemicals. Nature has already provided a model for many human-made devices, processes and mechanisms. Besides providing models, nature can serve as a guide to determine the appropriateness of our innovations in terms of durability, performance, and compatibility. Biomimetics involve many challenges, where the author's armwrestling challenge announced in 1999 has taken the human muscle as a baseline for the development of artificial muscles. This is still a challenge even after the competition that was held in 2005, however, advances towards making such arms are helping the field of biomimetic greatly.

For the question "what else can we learn from nature?" it would be highly helpful to build a documented database that would examine biology from an engineering point of view and catalogue nature inventions. This catalogue needs to include also the inventions that have already been used to possibly offer different angles of looking at nature's innovations to enrich other fields that have not benefited yet. This catalogue can be documented in a format of webpage hyperlinks that is crosslinking related information.

The inspiration of nature is expected to continue leading to technology improvements and the impact is expected to be felt in every aspect of our lives. Some of the solutions may be considered science-fiction in today's capability, but as we improve our understanding of nature and develop better capabilities this may become an engineering reality that is closer than we think.

ACKNOWLEDGEMENT

Research reported in this manuscript was conducted at the Jet Propulsion Laboratory (JPL), California Institute of Technology, under a contract with National Aeronautics and Space Administration (NASA).

REFERENCE

Agrawal R. N., M. Humayun, J. Weiland, G. Lazzi, and K. Gosalia, "Interfacing Microelectronics and the Human Visual System," Chapter 17, in [Bar-Cohen, 2005], pp. 427-447.

Bar-Cohen Y., (Ed.), "Biomimetics - Biologically Inspired Technologies," CRC Press, ISBN 0849331633, (Nov. 2005), pp. 1-527.

Bar-Cohen Y., "Electroactive Polymer (EAP) Actuators as Artificial Muscles - Reality, Potential and Challenges," 2nd Edition, ISBN 0-8194-5297-1, SPIE Press, Bellingham, WA, USA, Vol. PM136, (March 2004), pp. 1-765

Carlson J., S. Ghaey, S. Moran, C. Tran, D. L. Kaplan, "Biological Materials in Engineering Mechanisms," Chapter 14, in [Bar-Cohen, 2005], pp. 365-379.

Gordon, J.E. "The New Science of Strong Materials, or Why You Don't Fall Through the Floor" 2nd Ed. London: Pelican-Penguin, ISBN: 0140209204, (1976) pp. 1-287.

Mann S. (Ed.), *Biomimetic Materials Chemistry, Wiley Publishers,* ISBN: 0-471-18597-3, (1995) pp. 1-400.

Musallam S., B. D. Corneil, B. Greger, H. Scherberger and R. A. Andersen, "Cognitive Control Signals for Neural Prosthetics," Science, 305, (9 July 2004), pp. 258 – 262

Mussa-Ivaldi S., "Real Brains for Real Robots," Nature, Vol. 408, (16 November 2000), pp. 305-306.

Schmitt O. H., "Some Interesting and Useful Biomimetic Transforms," Proceeding, Third International Biophysics Congress, Boston, Mass., Aug. 29-Sept. 3,1969, p.297.

Serruya M.D., N.G. Hatsopoulos, L. Paninski, M.R. Fellows, and J.P. Donoghue, "Instant neural control of a movement signal," Nature, 416 (6877), Mar 14, 2002, pp. 141-142.

Stahlberg R. and M. Taya "Nastic structures – the enacting and mimicking of plant movements," Chapter 19, in [Bar-Cohen, 2005], pp. 473-493.

Szema R. and L. P. Lee, "Biologically Inspired Optical Systems," Chapter 11, in [Bar-Cohen, 2005], pp. 291-308.

Vincent J. F. V., "Stealing Ideas from Nature," Chapter 3 in Deployable structures, Springer-Verlag, Vienna, Pellegrino S. (Ed.), 2001, 51-58

Wessberg J., C. R. Stambaugh, J. D. Kralik, P. D. Beck, M. Lauback, J.C. Chapin, J. Kim, S. J. Biggs, M. A. Srinivasan and M. A. Nicolelis, "Real-time Prediction of Hard Trajectory by Ensembles of Cortical Neurons in Primates," Nature, Vol. 408, (16 November 2000), pp. 361-365.