Biomimetic Actuators using Electroactive Polymers (EAP) as Artificial Muscles

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Abstract.
Evolution has resolved many of nature's challenges leading to lasting solutions with maximal performance and effective use of resources. Nature's inventions have always inspired human achievements leading to effective materials, structures, tools, mechanisms, processes, algorithms, methods, systems and many other benefits. The field of mimicking nature is known as Biomimetics and one of its topics includes electroactive polymers that gain the moniker artificial muscles. Integrating EAP with embedded sensors, self-repair and many other capabilities that are used in composite materials can add greatly to the capability of smart biomimetic systems. Such development would enable fascinating possibilities potentially turning science fiction ideas into engineering reality.

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

NATURE AS AN INSPIRING MODEL

Nature is the largest laboratory that ever existed and ever will. In addressing its challenges through evolution it tested every field of science and engineering leading to inventions that work well and last. Nature has "experimented" with various solutions and over billions of years it has improved the successful ones. Nature has always served as a model for mimicking and inspiration to humans in their efforts to improve their life [Bar-Cohen, 2005; Vincent 2001]. By adapting mechanisms and capabilities from nature, scientific approaches have helped humans understand the related phenomena and the associated principles in order to engineer novel mechanisms and improve their capability. The subject of copying, imitating, and learning from biology was coined *Biomimetics* by Otto H. Schmitt [1969]. This field is increasingly involved with emerging subjects of science and engineering and it represents the studies and imitation of nature's methods, designs and processes.

As a model for inspiration, it is important to remember that Nature solutions are driven by survivability of the fittest and these solutions are not necessarily optimal for the technical performance. Effectively, all organisms need to do is to survive long enough to reproduce. 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. Nature evolution involves experimenting with the principles of physics, chemistry, mechanical engineering, 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, as in the case of bacteria and virus, to the macro and mega, including our life scale and the dinosaurs, respectively.

Inspiration of biomimetics is effective not only in making useful devices and mechanisms - the use of biologically inspired terms helps greatly in providing user friendly description of various concepts and terms. For example, 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. Architecture has benefited from inspiration of nature in making important landmarks such as the theaters in Sidney, Australia using the shapes of sea shells and the theater in Singapore using the durian fruit as a model for its building shape.

MATERIALS AND PROCESSES

The body is a chemical laboratory that processes chemicals that it acquires from nature and produces energy, construction materials, multifunctional structures [Nemat-Nasser et al. 2005; and Mann, 1995] and waste. Natural materials were well recognized by humans as source of food, clothing, comfort, and many other applications where, to name few, one can include fur, leather, honey, wax, milk and silk [Carlson et al. 2005]. 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, durability and multifunctionality. Many man-made materials are processed by heating and pressurizing, and this is in contrast to nature which always uses ambient conditions. Materials, such as bone, collagen or silk are made inside the organism's body without the harsh treatment that is used to make our materials. The fabrication of biologically derived materials produces minimum waste where the result is biodegradable and is recycled by nature. Learning how to process such materials can make our choices greater and improve our ability to create recyclable materials that can better protect the environment. Mimicking nature materials will also allow constructing improved prosthetics, where increasingly artificial parts such as hips, teeth, structural support of bones and others are being produced.

As specific examples one can observe the performance of the spider, which is one of biology's best "manufacturing engineers" with incredibly effective material-fabrication capability. The produced fibers are very strong, insoluble, continuous lightweight fiber and it 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 a trap for insects. 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. It is common to see webs tied in various shapes (including flat) between distant trees and the web is amazingly larger compared to the size of the spider. 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. Even though it is produced at room temperature and pressure, the spider's silk is much stronger than steel. The tensile strength of the radial threads of spider silk is 1,154 MPa while steel is 400 MPa [Vogel, 2003]. The spider eats flies and turns them with its digestion system to the silk that comes out from its back end and spooled as it is produced while preparing its web for trapping insects. This web is designed to catch insects that cross the net and gets stuck as a result of the net's sticky material and complexity. While the net is quite effective for catching insects, the spider is able to maneuver on it without the risk of being caught in its own trap. Recent progress in nanotechnology is showing promise for making fibers that are fine, continuous and with enormous strength. For this purpose, an electrospinning technique was developed [Dzenis, 2004] that allows producing 2-μm diameter fibers from polymer solutions or melts in high electric fields. The resulting nano-fibers were found to be relatively uniform and do not require extensive purification.

STRUCTURES AND TOOLS

Biological creatures can build amazing shapes and structures using materials in their surroundings or materials that they produce. Within a give species, the shapes and structures that are produced are very close copies. They are also quite robust and support the structure’s required function over the duration that it is needed. Such structures include the birds' nest and the bees' honeycomb. Often the size of a structure can be significantly larger than the species that built it, as is the case with the spider’s web. One creature that has a highly impressive engineering skill is the beaver, which constructs dams as its habitat on water streams. Other interesting structures include underground tunnels that gophers and rats build. Birds make their nest from twigs and other materials that are secured to various stable objects, such as trees, and their nests are durable throughout the bird's nesting season. Many nests are hemispherical in the area where the eggs are laid. One may wonder how birds have the capability to design and produce the correct shape and size that matches the requirements of allowing laid eggs to hatch and grow as chicks until they leave the nest. The nest’s size accounts for the potential number of eggs and chicks, in terms of required space. Even plants offer engineering inspiration, where mimicking the concept of seeds that adhere to an animal's fur, Velcro was invented and has led to an enormous impact in many fields, including clothing and electric-wires strapping. Because of their intuitive characteristics, the use of biologically-based rules allows for the making of devices and instruments that are user friendly where humans can figure out how to operate them using minimal instructions. While honeybees use their honeycomb for its efficient packing structure, 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.

ROBOTICS EMULATING BIOLOGY

The introduction of the wheel has been one of the most important human inventions. It allowed humans to traverse great distances and perform tasks that would have been otherwise impossible within the life time of a single human being [Bar-Cohen and Breazeal, 2003]. 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. Obviously, 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. Mobility using legged mechanisms for walking is currently being done via motors as the actuators. While motors have numerous advantages they have mass, complexity and many other limitations. Recent emergence of capable electroactive polymers (EAP), which are also known as artificial muscles, has enabled new possibilities with potential of turning science fiction to engineering applications [Bar-Cohen, 2004].

ARTIFICIAL MUSCLES

Polymers that can be stimulated to change shape and size have been known for many years. The activation mechanism of such polymers 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 the practicality of electrical stimulation, as well as the improved capabilities, make the electroactive polymers (EAP) one of the most attractive among the activatable polymers [Bar-Cohen 2003, 2004 and 2005].

EAP can be divided into two major categories based on their activation mechanism including ionic and electronic (Table 1). The electronic EAP, such as electrostrictive, electrostatic, piezoelectric, and ferroelectric, are driven by Coulomb forces. This type of EAP materials can be made to hold the induced displacement while activated under a DC voltage, allowing them to be considered for robotic applications. These materials have a greater mechanical energy density and they can be operated in air with no major constraints. However, the electronic EAP require a high activation fields (>100-V/μm) that may be close to the breakdown level. In contrast to the electronic EAP, ionic EAP are materials that involve mobility or diffusion of ions and they consist of two electrodes and electrolyte. The activation of the ionic EAP can be made by as low as 1-Volt and mostly a bending displacement is induced. Examples of ionic EAP include gels, polymer-metal composites, conductive polymers, and carbon nanotubes. Their disadvantages are the need to maintain wetness and they pose difficulties to sustain constant displacement under activation of a DC voltage (except for conductive polymers). Also, their sustain hydrolysis when the voltage is above 1.23V.

TABLE 1: List of the leading EAP materials

Electronic EAP	**Ionic EAP**
Dielectric EAP	• Carbon Nanotubes (CNT)
Electrostrictive Graft Elastomers	• Conductive Polymers (CP)
Electrostrictive Paper	• ElectroRheological Fluids (ERF)
Electro-Viscoelastic Elastomers	• Ionic Polymer Gels (IPG)
Ferroelectric Polymers	• Ionic Polymer Metallic Composite (IPMC)
Liquid Crystal Elastomers (LCE)	

The induced displacement of both the electronic and ionic EAP can be designed geometrically to bend, stretch or contract. Any of the existing EAP materials can be made to bend with a significant bending response offering an actuator with an easy to see reaction. However, bending actuators have relatively limited applications due to the low force or torque that can be induced. EAP materials are still custom made mostly by researchers and they are not available commercially. To help in making these materials widely available, the author established a website that provides fabrication procedures for the leading types of EAP materials and also information about custom purchase of such materials. This website is accessible via his EAP webhub http://eap.jpl.nasa.gov that includes links to many EAP related topics.

Turning EAP materials to actuators-of-choice requires having a well established infrastructure [Bar-Cohen, 2004]. This involves improving the understanding of the basic principles that drive the various EAP materials. Also, it is necessary to have effective computational chemistry models, comprehensive material science, electro-mechanics analytical tools and material processing techniques. Efforts are underway to gain a better understanding of the parameters that control the EAP electro-activation force and deformation. The processes of synthesizing, fabricating, electroding, shaping and handling are being refined to maximize the EAP materials actuation capability and robustness. Methods of reliably characterizing the response of these materials are being developed and efforts are being made to establish database with documented material properties in order to support design engineers that are considering the use of these materials. The author believes that an emergence of a niche application that addresses a critical need will significantly accelerate the transition of EAP from novelty to practical actuators. In such case, the uniqueness of these materials will need to be exploited and commercial products will emerge in spite of the current limitations of EAP materials.

Unfortunately, EAP-based actuators are still exhibiting low force below their efficiency is still limited. In 1999, the author challenged the world's researchers and engineers to develop a robotic arm that is actuated by artificial muscles to win a wrestling match against a human opponent. The match's objectives 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 (see Figure 1). 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.

CONCLUSIONS

After millions of years of evolution, nature developed inventions that work, which are appropriate for the intended tasks and that last. 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. 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 a reality that is closer than we think.

Artificial muscles, i.e., EAP materials, are one of the emerging fields of Biomimetics. For many years, these materials received relatively little attention due to their limited actuation capability and the small number of available materials. In the last fifteen years, a series of new EAP materials have emerged that exhibit large displacement in response to electrical stimulation. This capability of these new materials is making EAPs attractive as actuators for their operational similarity to biological muscles, particularly their resilience, quiet operation, damage tolerance, and ability to induce large actuation strains (stretching, contracting or bending). The application of these materials as actuators to drive various manipulation, mobility, and robotic devices involves multi-disciplines including materials, chemistry, electromechanics, computers, and electronics. Even though the force of actuation of existing EAP materials and their robustness require further improvement, there has already been a series of reported successes in the development of EAP-actuated mechanisms. Using EAP to replace existing actuators may be a difficult challenge and therefore it is highly desirable to identify a niche application where EAP materials would not need to compete with existing technologies.

FIGURE 1: An EAP driven arm made by students from Virginia Tech and the human opponent, 17-year old student

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