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PERSPECTIVE

Biomimetics—using nature to inspire human innovation

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Abstract

Evolution has resolved many of nature's challenges leading to lasting solutions. Nature has always inspired human achievements and has led to effective materials, structures, tools, mechanisms, processes, algorithms, methods, systems, and many other benefits (Bar-Cohen Y (ed) 2005 *Biomimetics—Biologically Inspired Technologies* (Boca Raton, FL: CRC Press) pp 1–552). This field, which is known as biomimetics, offers enormous potential for inspiring new capabilities for exciting future technologies. There are numerous examples of biomimetic successes that involve making simple copies, such as the use of fins for swimming. Others examples involved greater mimicking complexity including the mastery of flying that became possible only after the principles of aerodynamics were better understood. Some commercial implementations of biomimetics, including robotic toys and movie subjects, are increasingly appearing and behaving like living creatures. More substantial benefits of biomimetics include the development of prosthetics that closely mimic real limbs and sensory-enhancing microchips that are interfaced with the brain to assist in hearing, seeing and controlling instruments. A review is given of selected areas that were inspired by nature, and an outlook for potential development in biomimetics is presented.

Introduction

The term biomimetics, which was coined by Otto H Schmitt (Schmitt 1969), represents the studies and imitation of nature's methods, mechanisms and processes. Nature's capabilities are far superior in many areas to human capabilities, and adapting many of its features and characteristics can significantly improve our technology (Bar-Cohen 2005, Vincent 2001). Creatures in nature, if viewed as engineering designs, have general features rather than designs with specifications that are exact duplicates. As opposed to man-made designs that require exact duplication, creatures are able to perform quite well while having an identity that distinguishes one member from another in the same species. In contrast, our commercial products are sought to be duplicated 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 characteristic of biological systems. If we are successful in making biomimetic structures that consist of multiple cells, we may be able to design devices and mechanisms that are currently considered science fiction. Emerging nanotechnologies increasingly enhance the potential of such capabilities. Humans have learned much from nature and the results have helped surviving generations and continue to secure a sustainable future.

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 micro to macro and mega. Living systems archive the evolved and accumulated information by coding it into the species' genes and passing the information from one generation to another through

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Figure 1. The desire to fly was implemented using aerodynamic principles leading to enormous capabilities such as the supersonic passenger plane, the Concorde (photographed by the author at the Boeing Aerospace Museum, Seattle, WA).

Figure 2. The sensitive fern has its leaves open (left) until they are touched (right).

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.

Adapting ideas from biology can involve copying the complete appearance and function of specific creatures, as in toy manufacture where simplistic imitations are increasingly being incorporated to form electromechanized toys such as dogs that walk and bark, frogs that swim, and 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 seals. Once human flying became feasible, improvements in aircraft technology led to capabilities that far exceed any creature living on earth (see the example in figure 1).

Biological materials (Carlson *et al* 2005) have capabilities that surpass those of man-made ones and these include silk, leather and wool that are widely used to make clothing. Further, biologically made structures have numerous advantages and the honeycomb is one such example. Bees create the honeycomb for its efficient packing configuration and, for its low weight and high strength, the same structural shape of the honeycomb is used to produce many aircraft parts. Generally, there is no evidence that the man-made structure was copied from nature (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 the honeycomb configuration.

Plants also offer ideas for imitation and they have evolved in various ways, with some that produced uncommon solutions to their special needs (Stahlberg and Taya 2005). In addition to their familiar characteristics, some plants exhibit actuation capabilities that we would expect from biological creatures. Such plants include mimosa and sensitive fern (*onoclea sensibilis*) that bend their leaves when touched (see figure 2). There are also bug-eating plants with a leaf-derived trap that closes the 'door' locking unsuspecting bugs that enter the cage and become prey. 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.

Biology as a model

Nature has an enormous pool of inventions that passed the harsh test of practicality and durability in changing environment. In order to harness the most from nature's capabilities, it is critical to bridge between the fields of biology and engineering and to see cooperation of experts

Table 1. Characteristic similarities of biology and engineering systems.

Biology	Engineering	Bioengineering, biomimetics, bionics and biomechanics
Body	System	Systems with multifunctional materials and structures are developed emulating the capability of biological systems
Skeleton and bones	Structure and support struts	Support structures are part of every man-made system
Brain	Computer	Advances in computers are being made emulating the operation of the human brain
Intelligence	Artificial intelligence	There are numerous aspects of artificial intelligence that have been inspired by biology including augmented reality, autonomous systems, computational intelligence, expert systems, fuzzy logic, etc
Senses	Sensors	Computer vision, artificial vision, radar, and other proximity detectors all have direct biological analogies. However, at their best, the capability of the man-made sensors is nowhere near as good as biosensors
Muscles	Actuators	Electroactive polymers are actuators with functional similarity to natural muscles
Electrochemical power generation	Rechargeable batteries	The use of biological materials to produce power will offer mechanical systems enormous advantages

from both fields. This bridging effort can help in turning nature's capabilities into engineering capabilities, tools and mechanisms. In order to approach nature in engineering terms, it is necessary to sort biological capabilities along technological categories. Namely, one can take biologically identified characteristics and seek an analogy in terms of engineering as shown in table 1.

Some of nature's capabilities can 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 inspiring capability 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 with self-healing. One of the challenging capabilities will be to create miniature devices that can

- fly with enormous maneuverability like a dragonfly;
- adhere to smooth and rough walls like a gecko;
- adapt to the texture, patterns and shape of the surrounding environment like a chameleon, or reconfigure their body to travel through very narrow tubes like an octopus;
- process complex three-dimensional (3D) images in real time;
- recycle mobility power for highly efficient operation and locomotion;
- self-replicate, self-grow using resources from the surrounding;
- 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, significant progress has been made.

The various aspects of biology that were used to inspire man-made technologies are discussed in the following section and they show the enormous progress that has been made.

Artificial intelligence (AI)

The operation of the brain is emulated in the field of artificial intelligence (AI), which is a term that was coined in 1956. AI is a branch of computer science that studies the computational requirements for tasks such as perception, reasoning and learning, to allow the development of systems that have these capabilities (Russell and Norvig 2003). According to the American Association for Artificial Intelligence (AAAI), artificial intelligence (AI) is: "the scientific understanding of the mechanisms underlying thought and intelligent behavior and their embodiment in machines". AI researchers are addressing a wide range of problems that include studying the requirements for expert performance of specialized tasks, explaining behavior in terms of low-level processes, using models inspired by the computation of the brain and explaining them in terms of higher level psychological constructs such as plans and goals. The field seeks to advance the understanding of human cognition (Hecht-Nielsen 2005), understand the requirements of intelligence in general, and develop artifacts such as intelligent devices, autonomous agents and systems that cooperate with humans to enhance their abilities. AI technologies consist of an increasing number of tools, including artificial neural networks, expert systems, fuzzy logic and genetic algorithms (Luger 2001, Lipson 2005, Drezner and Drezner 2005). Increasingly, AI components are embedded in devices and machines that combine case-based reasoning and fuzzy reasoning to operate automatically or even autonomously. AI systems are used for tasks such as identifying credit card fraud, pricing airline tickets, configuring products, aiding complex planning tasks and advising physicians. AI is also playing a growing role in corporate knowledge management, facilitating the capture and reuse of expert knowledge.

Biologically inspired mechanisms

There are numerous examples of mechanisms that were inspired by observing biology; several examples are given herein.

Inchworm linear motors

The biologic inchworm is a caterpillar of a group of moths called *Geometridae*, which has six front legs and four rear legs. Emulating the mobility mechanism of this larva, or caterpillar, led to the development of motors and linear actuators that are known as *inchworms*. These commercially available motors are driven by piezoelectric actuators (made by companies such as Burleigh Instruments) and they are capable of moving at a speed of about 2 mm s^{-1} with a resolution of nanometers while providing hundreds of millimeters of traveling. The forces produced by these types of motors can reach over 30 N with zero backlash and high stability. Their non-magnetic content offers advantages for applications in test instruments such as magnetic resonance imagers (MRI). As opposed to biological muscles, the piezoelectric actuated inchworms have zero-power dissipation when holding position. Inchworm mechanisms have many configurations where the unifying drive principle is the use of two brakes and an extender. These motors perform cyclic steps where the rear brake clamps onto a shaft and an extender pushes the front brake forward. Then the front brake clamps the shaft releasing the rear brake and retracting the extender to move one step forward and this step can be as small as 1 nm.

Pumping mechanisms

Pumping mechanisms in nature offer a great model for fluid and gas pumping devices. Nature uses various pumping mechanisms that are also used in mechanical pumps. The lungs pump air in and out (tidal pumping) via the use of the diaphragm that enables our breathing with the support of the inter-rib muscles. Peristaltic pumping is one of the most common forms of pumping in biological systems, where liquids are squeezed in the required direction (Wu *et al* 2005). Such pumping is common in the digestive system. Pumping via valves and chambers that change volume is found in human and animal hearts, with expansion and contraction of chambers. The use of one-way valves is the key to the blood flow inside the veins, where the pressure is lower.

Controlled adhesion

Controlled wet or dry adhesion is achieved by many organisms. Using a highly fibrillated microstructure, the *Hemisphaerota cyanea* (a beetle) uses wet adhesion that is based on capillary interaction. On the other hand, the gecko exhibits remarkable dry adhesion using van der Waals forces. Even though these forces provide low intrinsic energy ($\sim$50 mJ m^{-2}), their effective localized application allow for the remarkable capability (Autumn *et al* 2002). Using this adhesion mechanism, the gecko can run on polished glass at a speed of about 1 m s^{-1} and attach its body to the wall using a single toe to support its body weight. This capability motivated efforts to mimic the gecko's adhesion mechanism and some limited success was reported. Such research was conducted by Autumn and Peattie (2003) who developed an artificial foot-hair tip model for a dry, self-cleaning adhesive that works under water and in vacuum.

Biologically inspired structures and tools

Biological creatures can build amazing shapes and structures using materials in their surroundings or materials that they produce. The produced structures are quite robust and support the required function over the duration the function 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. Birds make their nests 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. 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 the required space. Even plants offer engineering inspiration, where mimicking the concept of seeds that adhere to an animal's fur Velcro was invented and it has led to an enormous impact in many fields, including clothing and electric-wires strapping. Devices and instruments that are designed using biologically inspired rules are intuitive to operate by humans, which makes them user friendly and means they require minimal operation instructions. Examples of structures and tools that were most likely initiated from imitation of biological models are listed below. These examples illustrate the diverse and incredible number of possibilities that have already been mimicked.

Honeycomb

The honeycomb is made by bees in total darkness and it consists of a perfect hexagonal cellular structure that offers an optimal packing shape. For honeybees, the geometry meets their need for making a structure that provides the maximum amount of stable containment (honey, larvae) using the minimum amount of material. For the same reasons, the honeycomb is an ideal structure for the construction of control surfaces of an aircraft and it can be found in the wing, elevators, tail, the floor, and many other parts that need strength and large dimensions while maintaining low weight.

Fishing nets and screens

The fishing net can be viewed as another imitation of nature that most likely resulted from humans observing the spider using its web to catch flies. Even more basic, the concept of a fiber or string may have been inspired by the spider. Both the spider web and the fishing net have structural similarities and the same function of trapping passing-by creatures. The screen, mesh and sieving devices that allow separation of objects of various sizes may also be attributed to the evolution of the net.

Fins

Unlike the failure to fly when copying the flapping of birds' wings, the use of fins to enhance swimming and diving has been highly successful. While it may be arguable if fins were a direct biologically inspired invention, one can state that it is a common knowledge that swimming creatures have legs with gossamer (geese, swans, seagulls, seals, frogs, etc). Imitating the legs of these creatures offered the inventors of fins a model that was improved to the point that it resembles the leg of a seal and somewhat like the frog's leg. This similarity to the latter led to the naming of divers as frogmen, which is clearly a biomimetic-inspired name.

Composite materials

Structural materials that consist of fibers that are bonded by a matrix are known as composite materials and they are widely found in animals and plants. The combination of the fiber and matrix provides great stiffness, flexibility and low weight of the constructed structure. These properties of composite materials made them very attractive and they are now widely used in commercial parts and structures including fishing rods, tennis rackets and structural components of aircrafts.

Biological materials

The body is a chemical laboratory that processes chemicals acquired from nature and turns them into energy, construction materials, waste and various multifunctional structures (Mann 1995). Natural materials have been well recognized by humans as sources of food, clothing, comfort, etc, where, to name a 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 a 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 man-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 mostly 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.

Spider web—strong fibers

One of the biology's best 'manufacturing engineers' with an incredibly effective material-fabrication capability is the spider. It fabricates its web (figure 3) 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 a significant amount of water droplets from fog, dew or rain. Just in time 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 the web over great distances relative to its body. 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. 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 the production of 2 μm diameter fibers from polymer solutions or melts in high electric fields. The resulting nano-fibers were found to be relatively uniform and did not require extensive purification.

Figure 3. The spider constructs an amazing web that is made of silk material which for a given weight is five times stronger than steel.

Honeybee as a multiple materials producer

Another miniature 'material manufacturing engineer' found in nature is the honeybee. The bee is well known for making honey from nectar that it collects from flowers, but it also produces a honeycomb from wax. Historically, candles were made using this beeswax, but with the advent of the petroleum industry, candles are now mostly made from paraffin wax.

Multifunctional materials

Nature has made great efforts to use its resources effectively, and in addition to the use of power in efficient ways, including its recycling, nature also assigns multifunctions to its materials and structures. The use of materials that perform multiple tasks allows nature to make its creatures with a lower body weight. The concepts of multifunctional materials and structures are being studied by many researchers and engineers (Nemat-Nasser *et al* 2005) and have been the subject of a DAPRA program in the early 2000s. Increasingly, efforts are being made to emulate this characteristic where multiple disciplines are used including materials sciences, applied mechanics, electronics, photonics and manufacturing.

Biosensors

Living creatures are equipped with a sensory system, which provides input to the central nervous system about the environment around and within their body, and the muscles are commanded to act after analysis of the received information (Hughes 1999). Biological sensory systems are extremely sensitive and limited only by quantum effects (Szema and Lee 2005, Bialek 1987). These sensory systems are increasingly imitated, where we find our surroundings filled with sensors. Such sensors monitor our property from intruders, releasing soap and water when washing our hands, releasing hot air or paper towels to dry our hands, tracking our driving speed, observing our driving through intersections that are monitored by traffic lights, as well as many other applications. Similar to the ability of our body to monitor the temperature and keep it within healthy acceptable limits, our habitats, working and shopping areas have the environment control to provide us with comfortable temperatures. These examples are only a small number of the types of sensors that are used in our surroundings and the instruments that we use. Pressure, temperature, optical and acoustical sensors are widely in use and efforts are continuously being made to improve their sensing capability and reduce their size and the required power while mimicking ideas from biology. These include adapting principles from the eye to a camera, the whiskers of rodents as sensors for collision avoidance, and acoustic detectors that imitate the sonar in bats.

Other sensors that are being imitated include the sense of smell and taste. The topic of smell sensing has reached a level of interest and progress that led the researchers Linda B Buck and Richard Axel (1991) in 2004 to the Nobel Prize. The sense of smell is our analyzer of chemicals of airborne molecules allowing us to determine the presence of danger and hazardous chemicals, as well as gives us the joy of good food and other pleasant odors. Imitating the sensing capability of the nose offers important potential applications, and efforts to make such sensors have been explored since the mid-1980s. There are several devices that have been built and tested emulating the nose, where some of the devices use a chemical sensor array (Bartlett and Gardner 1999, Dickinson *et al* 1998, Nagle *et al* 1998). The technology is now at such a level that there are commercially available electronic noses, and they are applied for environmental monitoring and quality control in fields such as food processing.

While the sense of smell examines the chemical content of gases, the sense of taste is the biological chemical analyzer that examines dissolved molecules and ions and it uses clusters of receptor cells in the taste buds (Craven and Gardner 1996). Each taste bud has a pore that opens out to the surface of the tongue enabling molecules and ions to be taken into the mouth to reach into the receptor cells. Similar to the electronic nose, researchers explored the development of an electronic tongue that mimics the biological sensory capability (Vlasov and Legin 1998). Generally, the electronic tongue is an automatic system for analysis and recognition (classification) of liquids using sensor arrays, data acquisition elements and analytical tools. The result of E-tongue tests can be the identification of the sample, an estimation of its concentration or its characteristic properties. Using this technology allows the overcoming of the limitations of human sensing, including individual variability, inability to conduct online monitoring, subjectivity, adaptation, infections, harmful exposure to hazardous compounds and effect on the mental state. E-tongues are increasingly being used in applications such as monitoring food taste and quality, non-invasive diagnostics, searching for chemical/biological weapons, drugs and explosives, as well as environmental pollution monitoring.

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 lifetime of a single human being. While wheel-locomotion mechanisms allow great distances and great speeds to be reached, wheeled vehicles are subjected to great limitations with regard to traversing complex terrains 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. Also, operating robots as colonies or flocks is a growing area of robotic research. Creating robots that mimic the shape and performance of biological creatures has always been a highly desirable engineering objective. Searching the Internet with the keyword *robot* would identify many links to research and development projects that are involved with such robots. The entertainment and toy industries greatly benefited from advancement in this technology. Increasingly, robots are used in movies where creatures are shown to exhibit realistic behavior. Legged robots are even being developed for future NASA missions, and an example of such a robot is shown in figure 4.

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. The activation mechanism for such polymers can be electric, chemical, pneumatic, optical or 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 electroactive polymers (EAP) one of the most attractive among the mechanically activatable polymers (Bar-Cohen 2004, 2005a).

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^{-1}) 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

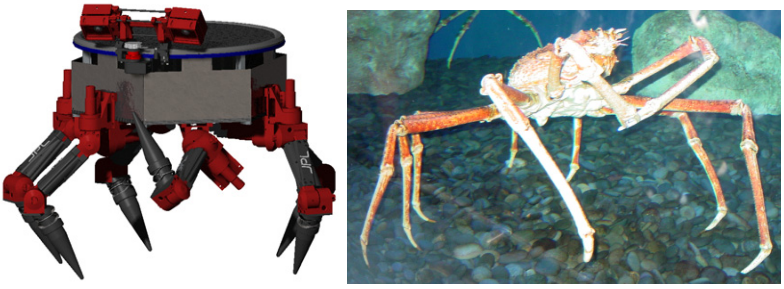

Figure 4. The six-legged robot, LEMUR (Limbed Excursion Mobile Utility Robot), which is developed at the Jet Propulsion Laboratory (Courtesy of Brett Kennedy, JPL) and the eight-legged crab in an aquarium.

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, ionometric polymer–metal composites (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 still exhibit 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, it is necessary to have an established EAP infrastructure. Effectively addressing the requirements of the EAP infrastructure involves developing its science and engineering basis; namely, understanding the mechanism of EAP materials' behavior, as well as 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 being 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 (moniker for EAP) 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 a human was held against a 17 year girl on 7 March 2005 and the girl won against three robotic arms that participated. One of the competing arms and the human opponent are shown in figure 5. Even though the arms did not beat the challenger, one of the arms was able to hold against the girl for 26 s and this is an important milestone.

Figure 5. An EAP driven arm made by students from Virginia Tech and the human opponent, a 17 year old student.

Defense and attack mechanisms in biology

A critical aspect of the survival of various species is having effective defense and attack mechanisms to protect against predators, catch prey, secure mating, protect the young generation, procure and protect food and other essential elements to survival. In today's era where there is a need for innovative measures to deal with homeland security issues, biomimetic concepts may enable us to further benefit from nature-inspired concepts, mechanisms and designs (Vincent 2005). The following are some of the biologically inspired mechanisms that were adapted by humans.

Camouflage

The chameleon and the octopus are well known for their capability to change their body color. The octopus matches the shape and texture of its surroundings as well as releases ink which completely masks its location and activity—although the octopus is a color-blind creature (Hanlon *et al* 1999). Generally, camouflage is not solely used for concealment, it also allows getting close to prey before charging ahead and capturing it by gaining the element of surprise while minimizing the response time of the prey. In some creatures, camouflage provides deterrence. For instance, some snakes, which are harmless, mimic the appearance of highly poisonous snakes. Further, some harmless flies camouflage themselves with bright colors, pretending that they are wasps. The camouflage capability of biological creatures has been the subject of imitation by all armies. In World War II, the zoologist Hugh Cott (1938) was instrumental in guiding the British army in developing camouflage techniques. Modern military uniforms and weapons are all colored in a way that makes them minimally visible by matching the background colors in the area where the personnel operate. Further, like the use of ink by an octopus, soldiers in the army and on large naval vessels at sea use a smoke screen when they do not want to be seen.

Body armor

The shell is another means of protection that some creatures are equipped with, both on earth and underwater. Creatures with a body armor include turtles, snails and various shelled marine creatures (e.g., mussels, etc). There are several forms of shells ranging from the shelter that is carried on the back (e.g., snails) to those with a full body cover in which case the creatures can completely close the shell as a means of defense against predators. While the snail is able to emerge from the shell and crawl as it carries the shell on the back, the turtle lives inside its ‘body armor’ and is able to use its legs for mobility when it is safe and hide the legs and head when it fears danger. The idea of body protection was adapted by humans many thousands of years ago in the form of hand-carried shields that allowed for defense against sharp objects, such as knives and swords. As the capability to process metals improved, humans developed better weapons to overcome the shield and therefore forced the need for a better body armor in order to provide cover for the whole body. The armor that knights wore for defense during the Middle Ages provided a metal shield from head to toe. In nature, the use of a shell for body protection is limited mostly to slow moving creatures and nearly all of them are plant-eaters. To overcome this limitation, humans modified the body armor concept to develop faster moving armored vehicles that provide both rapid mobile shield and weaponry for defense and offense capabilities.

Hooks, pins, sting, syringe, barbs and spears

Most of us have experienced at least once the pain of being hurt by a prick from plants—sometimes from something as popular and beautiful as the rose bush. Such experience can also occur when interacting with certain creatures, such as a bee. In the case of a bee, the stinger is left in the penetrated area (continuing to pump poison into the body) and does not come out because of its spear shape. Humans adapted and evolved the concept of sharp penetrators in order to create many tools for applications in medicine, sports and weaponry. These tools include the syringe, spears, fishing hooks, stings, barbs etc. Once penetrated, the hook and barb section on the head of a harpoon or an arrow makes it difficult to remove from the body of a fish, animal and the human body.

Decoy

The use of decoy is as ancient as the lizards’ use of its tail as a method to distract the attention of predators. The lizard autotomizes its tail and the tail moves rapidly, diverting the attention of the suspected predator while the lizard escapes to safety. This method is quite critical to lizards’ survival and the tail grows back again without leaving a scar. This capability is a great model for military strategies and also offers a model for potential healing of maimed parts of the human body. Success in adapting this capability could help some people with disabilities to possibly allow them to regrow amputated or maimed parts of their body.

Interfacing biology and machines

Interfacing between humans or animals and machines 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, Mussa-Ivaldi 2000) enabled this possibility where electrodes were connected to the brain of a monkey and, using brain waves, 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 other 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 the cursor on a computer monitor, where such devices translate signals from the brain’s motor cortex, the region that directs physical movement. Advances in this field have reached such a 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, MA (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 short-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. In addition to 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.

Interfacing of visualization and hearing devices and the human brain have already emerged where hearing devices are increasingly implanted and imaging devices are currently at advanced research stages (Szema and Lee 2005, Humayun *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 have already been 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, 3D 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 a performance that approaches that of the human eye. Also, researchers are working to create implants that can help the vision-impaired regain the ability to see (Humayun *et al* 2005). Increasingly, sophisticated visualization and image recognition are emerging in security systems. However, while lab demonstrations have been very successful, these systems still have recognition errors at an unacceptable level. 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.

Consideration of biomimetics for planetary application

For future space exploration applications, biomimetics offers a pool of concepts that can potentially be used to enable new technologies and enhance the available capabilities. To take advantage of the potential benefits to future NASA missions that can be harvested from mimicking from nature, Bar-Cohen *et al* (2004) used electroactive polymers and piezoelectric actuators and addressed the challenges to their application. As a potential application of these materials, one can envision that availability of strong and robust artificial muscles based on EAP materials may enable us in coming years to produce biomimetic legged robots that can run as fast as a cheetah, carry mass like a horse, climb steep cliffs like a gecko, reconfigure their body like an octopus, fly like a bird and dig tunnels like a gopher. This is an incredible vision for robots that can potentially be used to explore planets in the universe, and it may lead to future planetary mission plans that are based on a script for the robots operation following science fiction ideas. Some of the tasks that such robots may need to perform include autonomously operate to detect water, various resources, and possibly biological indicators in the search for past or present life or even construct facilities for future human habitats. Once such robots are made sufficiently reliable to operate in the harsh environment of space they will be able to act as human surrogates in executing tasks that require human's capabilities without subjecting real persons to any unnecessary hazards.

Space applications are among the most demanding in terms of the harshness of the operating conditions, requiring a high level of robustness and durability. Making biomimetic capability using electroactive material will potentially allow NASA to conduct missions on other planets using robots that emulate human operation ahead of the landing of humans. Generally, the requirements and challenges associated with making hardware based on the emerging technology for space flight are very difficult to overcome. However, since such applications usually involve producing only small batches, they can provide an important avenue for introducing and experimenting with new actuators and devices. This is in contrast to commercial applications, for which issues of mass production, consumer demand and cost per unit can be critical to the transfer of technology to practical use.

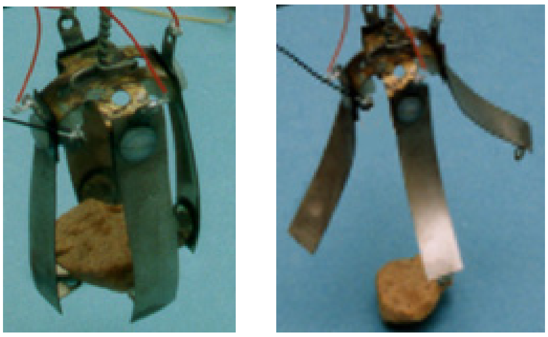

Figure 6. Four-finger EAP gripper lifting a rock similar to a human hand.

Advances in EAP towards making actuators with stronger force and higher displacement output will allow making capable legged robots and support the related research at the Jet Propulsion Laboratory (JPL), which is part of NASA. Generally, making biologically inspired robots that are driven by EAP actuators may have capabilities that are superior to natural creatures since these robots are not constrained by evolution and survival needs that are critical to biological creatures. To mimic a biological hand using simple elements, the author and his co-investigators constructed a miniature robotic arm that was lifted by an EAP actuator that is based on rolled dielectric elastomer and operated as a linear actuator. A gripper was mounted on the arm and it was constructed of four fingers consisting of IPMC-based EAP that operates as a bending actuator (Bar-Cohen 2005a). The linear actuator was used to raise and drop a graphite/epoxy rod. Further, the bending EAP fingers (see figure 6) were constructed to grab objects, such as rocks, very similar to the human hand. Significant challenges were encountered when using the IPMC for this application. These challenges included the requirement to maintain wetness, the difficulty to hold position of the fingers under dc voltage, residual deformation after activation and many other issues (chapter 21 in Bar-Cohen (2004)).

Telepresence combined with virtual reality using haptic interfacing offers another important potential for space applications particularly for avoiding the direct contact of humans with hazardous conditions. The author and his co-investigators used electrorheological fluids (ERFs) to explore the development of related haptic interfaces (Fisch *et al* 2003). ERF has the property of exhibiting increased viscosity when it is subjected to a higher electric field and the response is relatively fast (milliseconds). Using such an interface for a simulator aided by virtual reality can potentially benefit medical therapy in space and at distant human habitats. The probability that a medical urgent care procedure will be needed in future missions is expected to increase with the growth in duration and distance of manned missions. A major obstacle

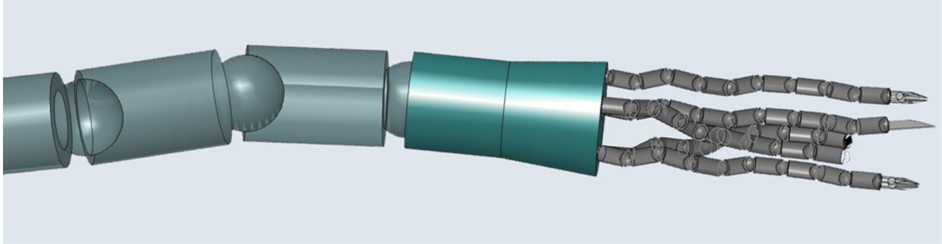

Figure 7. A graphic view of an octopus-configured catheter for surgical applications.

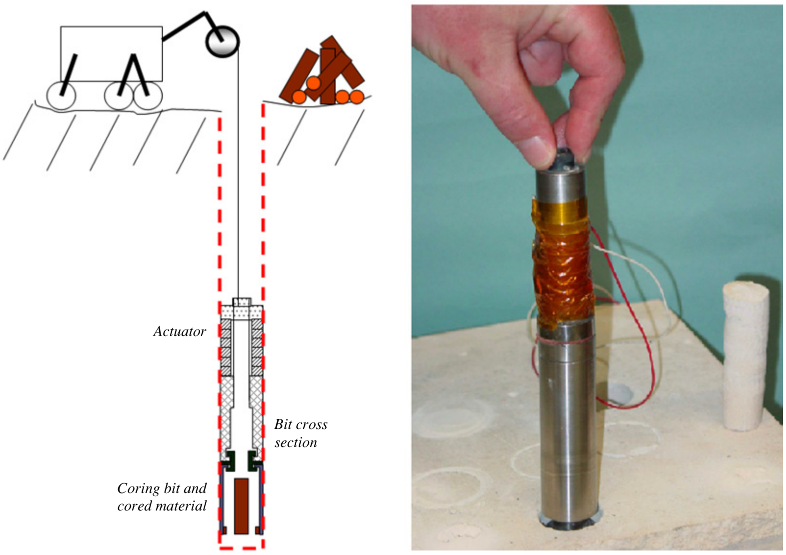

Figure 8. A schematic view of the gopher operating in a borehole, and a photographic view of the compact gopher and a formed core.

may arise as a result of the unavailability of onboard medical staff capable of handling every possible procedure that may be required. To conduct emergency treatments and deal with unpredictable health problems, the medical crews will need adequate tools and the ability to practice the necessary treatment at minimum risk to the astronauts. With the aid of all-in-one-type surgical tools and a simulation system, astronauts with medical background may be able to practice the needed procedures and later physically perform them. Medical staff in space may be able to sharpen their professional skill by practicing onboard simulated procedures or using new procedures that are downloaded from Earth. Generally, such a capability can also serve people who live in rural and other remote sites with no readily available full medical care capability. As an education tool employing virtual reality, training paradigms can be changed while supporting the trend in medical schools towards replacing cadaveric specimens with computerized models of human anatomy.

To minimize the use of invasive surgical procedures in planetary missions, there will be a need for extensive robotic capabilities. The increased medical use of robotics contributed significantly to reduction in mortality after surgery, faster recovery and minimized complications. An example of the existing robotics is the de Vinci surgical system that is becoming a standard tool in an increasing number of hospitals worldwide. Unfortunately, the current systems are quite large and do not allow for delicate surgical procedures as required, for example, in the brain. A novel design was conceived by the author and his research team, where a minimally invasive robotic arm as a surgical tool can be constructed in an octopus configuration with multiple degrees of freedom tentacles equipped with various tools. To implement such a possibility, a combination of EAP as actuators and electrorheological fluids (ERFs) was considered where the rigidity of such a flexible robotic arm can be controlled, and it can be operated as a haptic interface (Fisch *et al* 2003). A graphic illustration of such a futuristic concept is shown in figure 7 and it is biologically inspired using the octopus tentacle structure to establish capabilities that are impossible today (Bar-Cohen 2005b). The required EAP actuators can be based on the multifunctional electroelastomer roll (MER) actuators that were developed by SRI International (Kornbluh *et al* 2004). This actuator has a cylindrical shape and it is made of dielectric elastomer, which was demonstrated to produce 380% actuation strain. MER actuators were already demonstrated to generate high strain and moderate stress (up to 8 MPa). The response speed varies in a wide range from 1 Hz to as high as 20 kHz, depending on the type of elastomer material that is used and the amount of strain that is generated. One-degree-of-freedom (1-DOF), 2-DOF and 3-DOF spring rolls have been produced wherein the compliant electrodes are not patterned, are patterned on two, and are patterned on four circumferential spans, respectively.

Some of the challenges that are facing the users of EAP materials for space applications include the need to operate at low or high temperatures. Particularly, there is a great need for materials that can operate at temperatures that are close to −200 °C as on Titan and Europa or as high as 460 °C as on Venus. Another challenge is the need to develop large-scale EAP in the form of films, fibers, etc. The required dimensions can be as large as several meters or kilometers, and in such dimensions they can be used to produce large gossamer structures such as antennas, solar sails, and various large optical components. Future missions will need scaling of the components in order to reach capabilities at orders of magnitude higher than possible today. Using bulky materials that are made of metals or other heavy objects will be extremely costly to launch and the option of using inflatable thin polymer-based structures is quite attractive.

Another biomimetic application for planetary exploration that has been investigated by the author is the use of piezoelectric actuators for sample acquisition and handling. For over nine years, the author, members of his research group at JPL, and engineers from Cybersonics, Inc, have been involved with research and development of sampling techniques. The investigated techniques are mostly based on the use of piezoelectric actuators that drive a penetrator at the sonic-frequency range (Bar-Cohen 2005). Using the developed mechanism, which he called the Ultrasonic/Sonic Driller/Corer (USDC), a deep drill was developed that was inspired by the gopher and its method of creating tunnels in the ground (Bar-Cohen *et al* 2004). A piezoelectric actuator produces vibration in the form of a hammering action and the mechanism consists of a bit that has a diameter that is the same or larger than the actuator. The gopher is lowered repeatedly in a cycle that consists of penetration to the depth of the coring bit, breaking and holding the core, bringing the core to the surface, extracting it on the surface and returning to the deepened borehole to continue the process. A gopher with the coring bit inside a limestone and the core that was extracted are shown in figure 8.

Conclusions

After billions of years of evolution, nature developed materials, algorithms, structures and mechanisms that work, which are appropriate for the intended tasks and that last. The evolution of nature led to the introduction of highly effective and power efficient biological mechanisms. Failed solutions often led to the extinction of a specific species. In its evolution, nature archived its solutions in the genes of creatures that make up the 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, etc. Nature offers a model for us as humans in our efforts to 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 pollution biodegradable fibers, ceramics, plastics and various chemicals. Nature has already provided a model for many man-made devices, processes and mechanisms. In addition to providing models, nature can serve as a guide to determine the appropriateness of our innovations in terms of durability, performance and compatibility.

For the question 'what else can we learn?' it would be highly useful to build a documented database that would examine biology from an engineering point of view and to catalog nature capabilities. This catalog needs to include 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 database can be documented in a format of web-page hyperlinks, that is, cross-linking related information. Developing such a database will require adequate training in both engineering and biology. This will require cooperation between biologists and technologists/engineers as well as the establishment of such an education path in academic institutes that hopefully will also lead to new disciplines of biomimetic science and engineering.

The inspiration from 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 a reality that is closer than we think.

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