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Innovation inspired by nature: capabilities, potentials and challenges

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Abstract

Through evolution, nature came up with many effective solutions to its challenges and continually improving them. By mimicking, coping and being inspired, humans have been using Nature's solutions to address their own challenges. In recent years, the implementation of nature's capabilities has intensified with our growing understanding of the various biological and nastic mechanisms and processes. Successes include even the making of humanlike robots that perform such lifelike tasks as walking, talking, making eye-contact, interpreting speech and facial expressions, as well as many other humanlike functions. Generally, once humans are able to implement a function then, thru rapid advances in technology, capabilities are developed that can significantly exceed the original source of inspiration in Nature. Examples include flight where there is no species that can fly as high, carry so much mass, has so large dimensions and fly so fast, and operate at as such extreme conditions as our aircraft and other aerospace systems. However, using the capabilities of today's technology, there are many challenges that are not feasible to address in mimicking characteristics of species and plants. In this manuscript, state-of-the-art of biomimetic capabilities, potentials and challenges are reviewed.

Keywords: Biomimetics, Robotics, Sensors, Actuators, Biologically inspired technologies.

Introduction

Evolution has led to numerous capabilities that resulted from Nature's trial and error where the successful results were implemented, self-maintained and continually evolving to address posed challenges. The capabilities of biological and nastic systems have benefited from all the fields of science and engineering including physics, chemistry, mechanical engineering, materials science, and many others. Nature has always served as a model for humans' innovation and problems solving and in recent years this effort has turned to become a field of seeking to understand nature mechanisms and processes for copying, mimicking, and being inspired and the field gained the name Biomimetics [Bar-Cohen, 2005 and 2011; Benyus, 1989; Vincent, 2001]. Specifically, scientists are seeking rules, concepts and principles to inspire new manufacturing processes, materials, algorithms, mechanisms, and many other capabilities. The resulting benefits include improved structures, actuators, sensors, interfaces, drugs, and defense technologies. Generally, it is important to remember that Nature's solutions are the result of the survival of the fittest and the solutions are not necessarily optimal. To continue exist, organisms only need to survive long enough to reproduce.

The body of biological systems acts as a laboratory that processes chemicals from the surrounding to produce materials, energy, multifunctional structures, and waste [Mann, 1995]. Many of Nature's materials and processes are far superior to human-made ones and examples include the seashell and the spider web. Plants also made with many "inventions" and the most famous mimicked one is the adherence of seeds to animals' fur, which led to the invention of the Velcro and the numerous related applications including clothing and electric-wires strapping. The roots of plants are able to lift heavy structures as well as break rocks [Bar-Cohen, 2005 and 2011]. Moreover, plants distribute water and minerals evenly throughout their structure reaching great heights in giant trees and offering important model for mimicking.

Benefiting from the up-to-date advances in science and technology, we are significantly more able of studying the capabilities and functions of Nature's inventions. Generally, humans have not always applied what they knew about Nature's inventions and the camouflage is such an example. While it was known that camouflage is used by preys and predators to become stealth to each other, it was not fully used by armies until the beginning of the 20th century. It is interesting to note that even plants use such techniques, which include the fact that most unripe fruits are green minimizing their visibility until they reach proper readiness. Also, flowers are quite colorful making them highly visible to maximize their potential of being pollinated and fertilized.

Examining the various tools, clothing and capabilities that have been used by humans over thousand years ago, it can be interesting to find out if they were the result of humans' independent innovation, coincident similarity, or they were based on mimicking Nature. Obviously, Nature evolved many millions of years before humans reached the level of intelligence that was required to be able to mimic and produce tools. Initially, the mimicking was made in order to minimize the dependence on luck in finding food, shelter and life-essential resources. It is hard to believe that all the human-made solutions were purely independent inventions ignoring what was commonly seen in their neighborhood. For example, the need to feed their off-springs in cases of unavailability of the mother there was a critical need to develop effective alternative. This life-critical need has most likely inspired the development of the bottle with soft nipple making babies receptive. Also, the spider web probably inspired humans to develop wires, ropes, nets, sieves, screens and woven fabrics, and it is difficult to ignore the similarity to the fishing net, kitchen strainer, or even our clothing.

Biologically inspired technologies and mechanisms

There are many examples of biologically inspired technologies including artificial intelligence (AI), which mimic the operation of the brain. Increasingly, systems are operated "smarter" using AI algorithms such as knowledge capture, reasoning, and many others [Bar-Cohen and Breazeal, 2003], and are performing such tasks as perception, learning, and parallel processing that are critical to the operation of robots and other sophisticated systems.

Recognizing the advantages of nature materials, efforts have continually been made to produce artificial forms. It is interesting to note that natural materials are produced in ambient conditions while generating minimum waste and the results are biodegradable and recycled by nature. Learning how to mimic nature's materials and fabrication processes significantly increases the capabilities and choices of the available materials as well as simplifies their recycling and protects the environment. Further, it can benefit humans in such areas as the development of more life-like prosthetics, artificial hips, teeth, and others.

Biological structures are made either as an integral part of the body, including the bones, shells, and nails; or made by them to support the life essentials including bird nests, cocoon shells, spider web, and underground tunnels. These structures have numerous advantages such as resilience, multi-functionality, and great fracture toughness. For example, the bees produce the honeycomb that has a highly efficient packing configuration for laying their eggs with nurturing material (the honey) for their off-springs. On the other hand, the human made honeycomb is used to create aircraft structures that take advantage of the low weight and high strength (**Figure 1**).

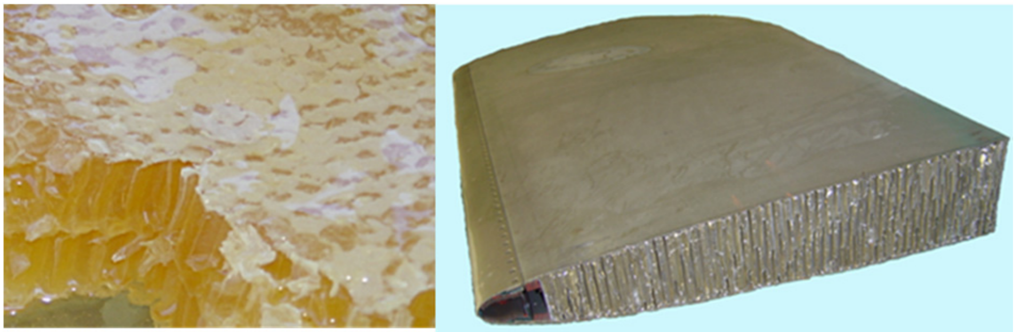

Figure 1: The honeycomb is now part of almost every aircraft. While it is similar to the one that is made by bees their functions are very different.

In biological systems, senses/receptors are providing inputs to the central nervous system about the environment around and within their body and the muscles are commanded to act based on the analysis of the received information. Biological sensory systems are extremely sensitive and limited by quantum effects. Similarly, sensors are critical to the ability of systems' to monitor their functions and allow for timely response to changing conditions. Pressure, temperature, optical and acoustical sensors are widely used and continuously being improved while reducing their size and consumed power.

The mobility of biological system is done by the muscles while in mechanical systems motors/actuators are used. Through evolution, biological muscles were optimized and are, effectively, the same mechanism in all the biological systems except for bacteria. They are driven by a complex linear mechanism that is capable of lifting large loads at short time response in the range of milliseconds [Full and Meijir, 2004]. Actuators have many limitations compared to muscles where electric motors have limited power density; hydraulic actuators are heavy and have low efficiency, and combustion engines are bulky and need to operate continuously. Further, mechanically activatable materials are widely used including shape memory alloys [Brailovski et al, 1999], electroactive polymers [Bar-Cohen, 2004], ferroelectric materials, and magneto-strictive compounds. There are significant challenges to applying such materials and, for example, piezoelectric actuators generate small displacements and require mechanical amplification to benefit from their high power densities [Sherrit et al, 2000].

The closest to mimic natural muscles are the electroactive polymers (EAP) and for this reason they are also widely known as "artificial muscles" [Bar-Cohen, 2004]. There are many types of EAP materials known today and most of them have emerged in the 1990s. To ease the understanding of their behavior, the author divided the various EAP materials into two groups distinguishing them by their operation mechanism: (a) Ionic EAP: These polymers consist of two electrodes and electrolyte. Electrical activation causes transport or diffusion of ions and leading to mechanical response. (b) Field-activated EAP: This EAP group is activated by the Coulomb force generated of an electric field between the electrodes of a polymer film. To help accelerate advances in this field, the author initiated and organized the annual international SPIE's EAP Actuators and Devices (EAPAD) Conference. At the opening of the first Conference that was held in 1999, the author posed a challenge to the worldwide scientists and engineers to develop a robotic arm that is actuated by artificial muscles to win an arm-wrestling match against a human opponent (see its icon in **Figure 2**). On March 7, 2005, the author organized the first arm-wrestling match with human (17-year old high school female student) as part of the EAP-in-Action Session of the EAPAD Conference (**Figure 3**). The student easily won against the participating three arms and the results demonstrated the weakness of the available EAP materials. If advances in EAP reach sufficiently high force, in a future conference a professional wrestler will be invited for another human/machine wrestling match.

Figure 2: The icon of the grand challenge for the development of EAP actuators.

Figure 3: An EAP driven arm made by students from Virginia Tech wrestling with the human opponent, 17-year old high school student.

Biomimetic mechanisms

Nature is filled with biological mechanisms and examples include pumping where the most common mechanism is peristaltic pumping having liquids squeezed towards the required direction. Breathing via our lungs is made by pumping air in a tidal process using diaphragm movement generated by the intercostal muscles. The heart is another example of biological pump where valves and volume changing chambers are used to control the blood flow thru the veins and arteries. Plants use capillary forces to pump water and minerals and distribute them evenly independent of the height, which can be many meters. As mentioned earlier, plants are capable of delivering very large forces via their roots and are capable of fracturing rocks and lifting slabs.

Generally, camouflage is the capability to blend with the terrain to become minimally visible (see example in **Figure 4**) as well as obtaining deterrence by creating illusion about the body dimensions. Examples of the latter include insects or animals making their body appear larger than their actual size, similarly, armies uses this tactic when fighting war against their enemies. Besides camouflage, predators use many other techniques to catch preys while the hunted animals use various defense mechanisms to avoid being discovered or captured. Some of the capabilities have already been duplicated in human-made tools while others are still a challenge to mimic. The suction caps, which are part of the octopus tentacles, are used to secure the grip onto captured preys and they are also widely used for mounting objects on smooth surfaces such as tiles and glass windows. In contrast, it is currently impossible to mimic the octopus incredible capability to match the color, pattern, shape and texture of adjacent objects as well as its ability to pass through narrow openings far smaller than its body's cross section. Mimicking these capabilities would allow developing robo-spy that can enter a room thru the gap under the door and minimize its visibility by matching the colors and texture of the floor covering. Making such a robo-cop may be used to find and catch wanted criminals and terrorists and hold onto suspects using tentacles.

Figure 4: Leafy seadragon has the shape of a plant allowing it to minimize its visibility

Ambulation mechanisms can be bio-inspired to achieve mobility in areas in which it is hard to traverse [Bar-Cohen, 2011]. Species are able to operate almost anywhere on Earth and, with fluidic performance, to travel great distances in highly varied environments. The Robo-Lobster is an example of a biomimetic robot that was designed to operate in hard to reach areas [Ayers and Witting, 2007]. This robot was developed for searching mines buried beneath beaches or floating in shallow waters. The conditions at the locations where mines are expected to be hidden are considered too harsh for the general types of marine creatures. In contrast, the biological lobster is able to operate in such environments and its mimicking potentially provides useful mine detection capabilities.

A potential biological inspiration model can be the ability of ants to identify food from great distance. Mimicking this capability, one may develop swarms of ant-like micro-robots that are equipped with artificial nose and continuously search for residues of explosives and illegal substances. Such robots may perform surveillance, notify the authorities and possibly perform critical explosive disabling functions.

Robotics as biomimetics beneficiary

Robots are electromechanical devices with biomimetic characteristics capable of performing complex tasks, operating in hard to reach areas and at conditions that are too harsh or dangerous for humans [Bar-Cohen]. When operating wheeled vehicles on paved roads, they are capable of moving at very high speeds using relatively low power, however, they are highly constrained in such terrains as dunes and steep cliffs. To operate in such terrains, legged robots are being developed and even being considered for space and military applications (see examples in **Figure 5** and **Figure 6**). The mimicking mobility of highly adaptive species, offers enormous potential including the ability to climb trees like monkey, run very fast like a cheetah, and hop to great heights and distances like the kangaroo.

The ultimate challenge to biomimetics is the mimicking of humans in the form of robots. As the capability to produce humanlike robots improves they are expected to enter our life in the form of either household appliances, or perhaps even human peers. Such robots may replace unskilled human labor as well as possibly be used to perform difficult and complex tasks in hazardous conditions. However, such humanlike machines may raise concerns, fear and dislike [Bar-Cohen and Hanson, 2009]. The Japanese roboticist Masahiro Mori [1970] hypothesized that as the degree of similarity between robots and humans increases there will be initial enthusiasm, but as the similarity becomes closer it will turn into strong rejection and dislike, and finally as the likeness becomes very close there will be favorable attitude shift. Mori [1970] described these attitude shifts graphically with a dip on a continuous curve and it has become known as the Uncanny Valley hypothesis. Critics do not accept this hypothesis as fact and they argue that it has never been proven by systematic experiment. Generally, sociable humanlike robots are increasingly being developed with impressive capabilities including verbally and facially express emotions as well as respond emotionally [Breazeal, 2002; Bar-Cohen and Hanson 2009]. As such robots become more useful and offer niche to its users, they are expected to become increasingly more desired products and the science fiction vision of seeing them at every home may become an engineering reality.

Figure 5: The Big-Dog (made by Boston Dynamics), which is a mull-like legged robot that was developed for military application. Photographed by the author.

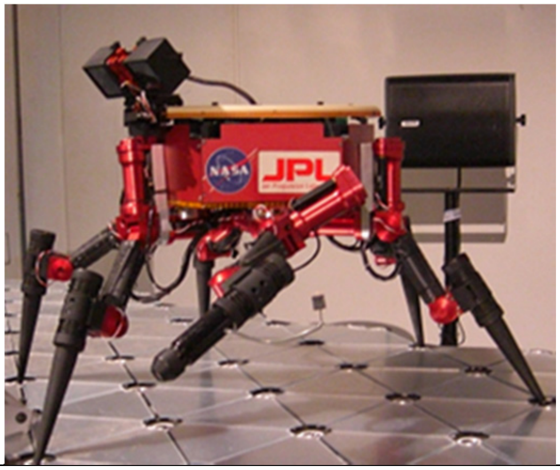

Figure 6: A 6-legged robot developed at JPL for potential application in future NASA exploration missions.

Medical application of biomimetics

The field of medicine is expected to be one of the major beneficiaries of biomimetics and many applications were already implemented. However, there are still many Nature's medically beneficial capabilities that are not possible to mimic yet and this includes lizards' ability to regrow its tail, which can incredibly heal disabled humans. The lizard sheds its tail as part of its defense mechanism where the rattling tail acts as a decoy to distract the attention of predators and allows the lizard to escape. Soon afterward the lizard's tail regrows back. Efforts to enable such a re-growth are underway including the use of extracellular matrix materials that sometimes triggers the regeneration of the desired organs. Also, the use of stem-cells is being investigated for such regeneration capabilities.

The ability of certain species to slow their body's metabolism to almost zero offers an important medical capability that if mimicked may provide military casualties and accident victims ability to survive until adequate medical assistance is available. Also, patients with terminal diseases may be kept alive till potential cure is developed. For example, by hibernating for as long as seven months, bears are able to survive extremely cold winters and lack of food. People who suffer kidney problems that require dialysis may benefit from mimicking the capability of the bear to hold the urine in the body for extended periods without damage to the body or causing health deterioration. Another type of dormancy state is the estivation or aestivation, which occurs during periods of extremely hot and dry conditions and it allows such species as the desert snails to survive up to 5 years without water.

Biomimetics – technology revolutions benefiting from mimicking evolution results

Evolution led to inventions that are great models for mimicking and inspiration of new technologies and it involved all the sciences and engineering disciplines, and a wide range of scales from as small as nanometers. Biomimetics offers many potential benefits to our life and it is becoming increasingly easier to mimic using emerging highly effective tools.

Design requirements of engineering structures are generally quite similar to those of biological systems. These include the need to produce low weight structures, consume minimal power, and have high durability over the life of the species or the product [Yen et al, 2011]. Failed design in biology leads to extinction of the specific species whereas in engineering the product or structure is retired from service and the design is modified or eliminated from use. Biomimetics may involve a simple copy and an example is the spider web that most likely led to the fabrication of the fishing nets. Others may provide inspiration such as the observation that many insects and birds are capable of flying, which suggested to humans that it can be done. However, achieving the capability to fly necessitated the development of the related critical knowledge and knowhow. As opposed to engineers' efforts to mass produce identical products at great precision to assure their reliability, nature produces duplicates of the same species with quite a bit of differences. In spite of the differences and imperfections, the individual members of specific species perform quite flawlessly and very similarly.

Sensors are critical to the operation of any system and the capability of biological senses and receptors offer many important possibilities that their mimicking can contribute to the state-of-the-art of systems. Examples of such senses are the ability of some species (such as certain fish, rodents, snakes and even toads) to sense upcoming nature's disasters including earthquake and tsunami. It is interesting to note that, in 2004, when the big tsunami hit the pacific region many animals fled to high grounds while humans did not have a clue about the meaning of the receding seawater and the disaster that followed.

Nature provides an important guide to living in harmony with it [Benyus, 1998]. As an example, plants use the CO_2 pollution to produce oxygen and converting it to life essential resources while harvesting solar energy in Earth friendly form. Increasingly, using our planet resources of solar energy, wind, ocean waves and many others, energy is being harvested in commercial green forms.

Implementing Nature's concepts may be used to transform science fiction ideas into engineering reality. There are many challenges to mimicking the capability of species including the making of octopus-like robots. Producing such a robot requires extremely high dexterity, intelligence and autonomy with the capability to traverse through very narrow openings; camouflage the body to match the colors, shape and texture of the surrounding; having multiple tentacles with adjustable rigidity for firm grabbing; using ink to form smoke screen; and simultaneously perform multiple tasks. The level of complexity and the challenges that are involved with mimicking nature can be further appreciated with the current impossibility of making robots that grow from a micron-size "seed" (as plants do) to a fully grown, active machine that operates autonomously. It is hard to predict what would be the next major mimicking but such fields as medical, military, consumer products, and many others may potentially benefit from revolutionary capabilities that biomimetics would enable. This suggests that it is important to preserve our planet's species and plants in order to assure that the inventions they harbor would be around when we improve our tools to better understand them.

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