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Making Science Fiction an Engineering Reality Using Biologically-Inspired Technologies

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ABSTRACT

For many years, the trend has been to automate processes in order to increase the efficiency of performing redundant tasks. Realizing that some parts are too complex to inspect with a simple automatic system robotic mechanisms were developed to perform the necessary complex tasks. Lab and field scanners have emerged with significant capabilities where manipulators and crawlers were developed for rapid and reliable inspection. One of the limiting factors that hampered the wide use of robotics for inspection of aircraft and other complex structures has been the economical aspect of handling small quantities of complex parts. Biologically inspired autonomous robots can potentially address the need to inspect structures with configuration that are not predetermined and with quality assessment that requires human-like judgment. The operation of these robots may take place at harsh or hazardous environments that are too dangerous for human presence. Making such robots with capabilities that used to be considered science fiction or wishful thinking is increasingly becoming an engineering reality. This paper reviews the state of the art and challenges to some of the biologically inspired technologies and the potential impact on the field of NDE.

INTRODUCTION

Throughout history, humans have always sought to mimic the appearance, mobility, functionality, intelligent operation, and thinking process of biological creatures. This field of biologically inspired technology (also known as biomimetics) ranges from making simple tools to the level of developing creature-like robots that operate with realistic behavior. Imagine a person walking towards you where suddenly you notice something weird about him – he is not real but rather he is a robot. Your reaction would probably be "I can't believable it but this robot looks very real" just as you would react to an artificial flower that is a good imitation. You may even proceed and touch the robot to check if your assessment is correct but, as oppose to the flower case, the robot may be programmed to respond physical and verbally to your proactive astonishment. This science fiction scenario could become a reality as the current trend continues in developing biologically inspired technologies [Bar-Cohen and Breazeal, 2003]. Towards realization of such technology, evolution have led to significant development in related fields that include artificial muscles, artificial intelligence, artificial vision as well as capabilities in materials science, mechanics, electronics, computing science, information technology and many others.

For many years, engineers developed automatic processes in order to increase the efficiency of performing redundant tasks. This effort led to the emergence of production lines with significantly reduced manufacturing cost and highly consistent product appearance and performance. The quality of produced parts has increasingly been improved as new methodologies and inventions were conceived and implemented. Since some parts are too complex to handle with a simple automatic system, robotic mechanisms have emerged. Some of the limiting factors that hampered the wide use of robotics were economical issues. Generally, robots were considered bulky and expensive machines with large arms that are used to process complex parts. As the technology evolved and powerful computers as well as effective control methodologies have been introduced, robots became more sophisticated and the possibilities of emulating biological systems became more feasible.

The field of NDE is increasingly benefiting from the advancement in robotics and automation [Bar-Cohen, 2000]. Crawlers and various manipulation devices are commonly being used to perform variety of inspection tasks from C-scan to contour following and other complex functions. At JPL (part of National Aeronautics Space Agency, NASA), a multifunctional automated crawling system (MACS) was developed to simplify the scanners that are used in the field establishing a mobility platform onto which various types of board level NDE instruments can be integrated (see Figure 1). This crawler uses two legs to "walk" on structures while adhering to wall surfaces similar to gecko. While this and other advancements were made to improve the speed and reliability of the inspection, having an on-site human operator is critically needed to assure the reliable operation of these robots. Making a robot that autonomously performs NDE tasks in biologically-like characteristics is still a challenge but with the current trend such a possibility may not be a too distant reality.

FIGURE 1: MACS is shown crawling on the C-5 aircraft [Bar -Cohen, 2000].

Searching the internet under the keyword robots would identify many links to reports that cover research and development projects related to the development of robots that are equipped with biologically like features. The entertainment and toy industries have greatly benefited of the advancement in this technology. Increasingly robots are used in movies showing creatures with realistic behavior and one can list such movies as AI, Bicentennial Man, and Blade Runners. Visiting toy stores one can easily see how far the technology progressed in making inexpensive toys that imitate biology – such store displays include frogs that swim in a fish bawl or dogs that walk back and forth or even bark. Operating robots that emulate the functions and performance of human or animal involves using actuators and mechanisms with state-of-the-art capabilities. Upper-end robots and toys are becoming increasingly sophisticated allowing them to walk and talk with some that can be operated autonomously and remotely reprogrammed to change their characteristic behavior. As this technology evolves it is becoming more likely to believe that in the future human-like robots may be developed to operate as artificial inspectors and perform tasks that are highly reliability and very repeatable with extremely low probability of errors and capable of working tirelessly without break. In spite of the success in making robots that mimic biology there is still a large gap between the performance of robots and nature creatures. The required technology is multidisciplinary involving the need for actuators that emulate muscles, smart control algorithms that involve artificial intelligence methodologies as well as many other technologies.

NATURE AS A BIOLOGICALLY-INSPIRING MODEL

Evolution over millions of years made nature to introduce solutions that are highly power-efficient and imitating them offers potential improvements of our life and the tools we use. Human desire and capability to imitate nature and particularly biology has continuously evolved and with the improvement in technology more difficult challenges are being considered. One of the early implementation of biologically inspired devices was the bicker of birds, which was adapted as a tool in the form of tweezers. More sophisticated inspirations include the development of aerodynamic structures and systems that use the shape of seeds. Trees disperse their seeds using various techniques where the use of aerodynamics allows them to self-propel with the aid of wind to carry the seeds to great distances. The shape of such seeds has inspired human to produce objects that can be propelled in air and those have evolved to the boomerang, gliders, helicopter blades and various aerodynamic parts of aircrafts. In Figure 2, an example is shown of a winged seed of the Tipuana Tipu tree (6.5-cm long) that is part of the landscape of many streets in such places as Southern California. Another plant that offered an inspiring design is the tumbleweed and it was suggested as a mobility method for operating on Mars using wind rather than a power consuming mechanism. Since wind is blown throughout Mars, producing a rover that imitates the tumbleweed offers an attractive option of designing a vehicle that can traverse great distances with a minimal use of power.

FIGURE 2: Seeds with aerodynamic shape are dispersed by wind to great distances

The introduction of the wheel has been one of the most important invention that human made allowing to travel great distances and perform tasks that would have been otherwise impossible within the life time of a single human being. While wheel locomotion mechanisms allow reaching great distances and speeds, wheeled vehicles are subjected to great limitations with regards to traversing complex terrain with 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. Making miniature devices that can fly like a dragonfly; adhere to walls like gecko; adapt the texture, patterns, and shape of the surrounding as the octopus (can reconfigure its body to pass thru very narrow tubing); process complex 3D images in real time; recycle mobility power for highly efficient operation and locomotion; self-replicate; self-grow using surrounding resources; chemically generate and store energy; and many other capabilities are some of the areas that biology offers as a model for science and engineering inspiration. While many aspects of biology are still beyond our understanding and capability, significant progress has been made.

ARTIFICIAL MUSCLES

One of the key aspects of making biologically inspired robots is the development of actuators that allow emulating the behavior and performance of real muscles. The potential for such actuators is increasingly becoming feasible with the emergence of the electroactive polymers (EAP), which also known as artificial muscles [Bar-Cohen, 2001]. These materials have functional similarities to biological muscles, including resilience, damage tolerance, and large actuation strains (stretching, contracting or bending). They can potentially provide more lifelike aesthetics, vibration and shock dampening, and more flexible actuator configurations. These materials may be used to eliminate the need for gears, bearings, and other components that complicate the construction of robots, which are responsible to their high costs, weight and premature failures.

The large displacement that can be obtained with EAP using low mass, low power and, in some of these materials also low voltage, makes them attractive actuators. The capability of EAPs to emulate muscles offers robotic capabilities that have been in the realm of science fiction when relying on existing actuators. Exploiting the properties of artificial muscles may enable even the movement of the covering skin to define the character of the robots and provide expressivity. As an example of an application, at JPL such EAP actuators were used to design and construct a miniature robotic arm (see Figure 3). This robotic arm illustrates some of the unique capability of EAP, where its gripper consisted of four bending type EAP finger-strips with hooks at the bottom emulating fingernails. This arm was made to grab rocks similar to human hand.

FIGURE 3: 4-finger EAP gripper lifting a rock.

The beginning of the field of EAP can be traced back to an 1880 experiment that was conducted by Roentgen using a rubber-band with fixed end and a mass attached to the free-end, which was charged and discharged [Roentgen, 1880]. Sacerdote [1899] followed this experiment with a formulation of the strain response to electric field activation. Further milestone progress was recorded only in 1925 with the discovery of a piezoelectric polymer, called electret, when carnauba wax, rosin and beeswax were solidified by cooling while subjected to a DC bias field [Eguchi, 1925]. Generally, there are many polymers that exhibit volume or shape change in response to perturbation of the balance between repulsive intermolecular forces, which act to expand the polymer network, and attractive forces that act to shrink it. Repulsive forces are usually electrostatic or hydrophobic in nature, whereas attraction is mediated by hydrogen bonding or van der Waals interactions. The competition between these counteracting forces, and hence the volume or shape change, can be controlled by subtle changes in parameters such as solvent, gel composition, temperature, pH, light, etc. The type of polymers that can be activated by non-electrical means include: chemically activated, shape memory polymers, inflatable structures, including McKibben Muscle, light activated polymers, magnetically activated polymers, and thermally activated gels [Chapter 1 in Bar-Cohen, 2001].

Polymers that are chemically stimulated were discovered over half-a-century ago when collagen filaments were demonstrated to reversibly contract or expand when dipped in acid or alkali aqueous solutions, respectively [Katchalsky, 1949]. Even though relatively little has since been done to exploit such 'chemo-mechanical' actuators, this early work pioneered the development of synthetic polymers that mimic biological muscles. The convenience and practicality of electrical stimulation and technology progress led to a growing interest in EAP materials. Following the 1969 observation of a substantial piezoelectric activity in PVF2 [http://www.ndt.net/article/yosi/yosi.htm], investigators started to examine other polymer systems, and a series of effective materials have emerged. The largest progress in EAP materials development has occurred in the last ten years where effective materials that can induce over 300% strains have emerged [Kornbluh and Pelrine, 2001].

As polymers, EAP materials can be easily formed in various shapes, their properties can be engineered and they can potentially be integrated with micro-electro-mechanical-system (MEMS) sensors to produce smart actuators. As mentioned earlier, their most attractive feature is their ability to emulate the operation of biological muscles with high fracture toughness, large actuation strain and inherent vibration damping. Unfortunately, the EAP materials that have been developed so far are still exhibiting low conversion efficiency, are not robust, and there are no standard commercial materials available for consideration in practical applications. In order to be able to take these materials from the development phase to application as effective actuators, there is a need to establish an adequate EAP infrastructure. Effectively addressing the requirements of the EAP infrastructure involves developing adequate understanding of EAP materials' behavior, as well as processing and characterization techniques.

The technology of artificial muscles is still in its emerging stages but the increased resources, the growing number of investigators conducting research related to EAP, and the improved collaboration among developers, users, and sponsors are expected to lead to rapid progress in the coming years. In 1999, the author posed a challenge to the worldwide research and engineering community to develop a robotic arm that is actuated by artificial muscles to win an arm wrestling match against a human opponent (Figure 4). Progress towards this goal will lead to significant benefits, particularly in the medical area, including effective prosthetics. Decades from now, EAP may be used to replace damaged human muscles, potentially leading to a "bionic human." A remarkable contribution of the EAP field would be to one day see a handicapped person jogging to the grocery store using this technology.

FIGURE 4: Grand challenge for the development of EAP actuated robotics.

MAKING ROBOTS ACTUATED BY EAP

Mimicking nature would immensely expand the collection and functionality of the robots allowing performance of tasks that are impossible with existing capabilities. As technology evolves, great number of biologically inspired robots actuated by EAP materials emulating biological creatures is expected to emerge. This type of robots may be programmed to take on such tasks as performing NDE procedures in hard to reach areas of aircraft structures. The challenges to making such a robot can be seen in Figure 5 where the robot is shown to hop and express joy. Both tasks are easy for human to do but are extremely complex to incorporate into a robot.

To promote the development of effective EAP actuators, which could impact future robotics, toys and animatronics, two platforms were developed. These platforms are available at the Principal authors lab at JPL and they include an Android head [Figure 6, and video on http://ndeaa.jpl.nasa.gov/nasa-nde/lommas/eap/EAP-web.htm] that can make facial expressions and a robotic hand with activatable joints. At present, conventional electric motors are producing the required deformations to make relevant facial expressions of the Android. Once effective EAP materials are chosen, they will be modeled into the control system in terms of surface shape modifications and control instructions for the creation of the desired facial expressions. Further, the robotic hand [Figure 7, and video on http://ndeaa.jpl.nasa.gov/nasa-nde/lommas/eap/EAP-web.htm] is equipped with tandems and sensors for the operation of the various joints mimicking human hand. The index finger of this hand is currently being driven by conventional motors in order to establish a baseline and they would be substituted by EAP when such materials are developed as effective actuators.

The easy capability to produce EAP in various shapes and configurations can be exploited using such methods as stereolithography and ink-jet printing techniques. A polymer can be dissolved in a volatile solvent and ejected drop-by-drop onto various substrates. Such processing methods offer the potential of making robots in full 3D details including EAP actuators allowing rapid prototyping and quick mass production [chapter 14 in Bar-Cohen, 2001]. Making insect-like robots could help inspection hard to reach areas of an aircraft engine where the robot creature can be launched to conduct the inspection procedure and to download the data upon exiting.

FIGURE 5: Biomimetic robot.

FIGURE 6: An android head (Photographed at JPL) as EAP platform will use such actuators to make facial expressions (Courtesy of D. Hanson, University of Texas, Dallas, who sculptured the head and instrumented it jointly with G. Pioggia, University of Pisa, Italy).

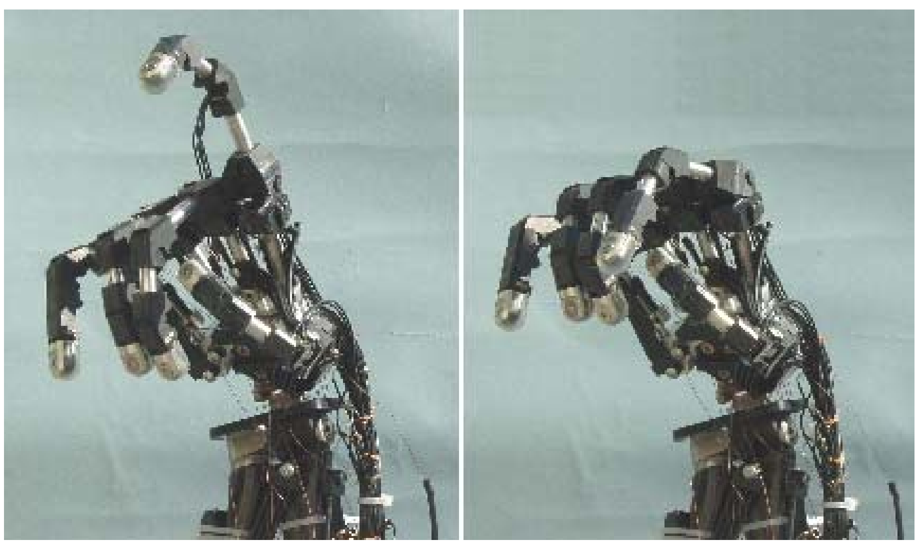

FIGURE 7: Robotic hand (Photographed at JPL) is available at JPL as a platform for demonstration of EAP actuators [Courtesy of Dr. Graham Whiteley, Sheffield Hallam U., UK. The actuators were installed by Giovanni Pioggia – University of Pisa, Italy/JPL].

REMOTE PRESENCE

Remotely operated robots and simulators that involve virtual reality and the ability to "feel" remote or virtual environment are highly attractive and offer unmatched capabilities [Chapter 4, Bar-Cohen and Breazeal, 2003]. To address this need, the engineering community has started developing haptic (tactile and force) feedback systems. Users of future NDE simulators may immerse themselves in the display medium while being connected thru haptic and tactile interfaces to allow them to "feel the inspection task" at the level of their fingers and toes. Thus, an expert can perform NDE procedures from the convenience of the office without having to be present at the operation site. Recently, the potential of making such a capability was enabled with the novel MEMICA system (MEchanical MIrroring using Controlled stiffness and Actuators) concept [http://ndeaa.jpl.nasa.gov/nasa-nde/memica/memica.htm]. For this purpose, scientist at JPL and Rutgers University used an EAP liquid, called Electro-Rheological Fluid (ERF), which becomes viscous under electro-activation. Taking advantage of this property, they designed miniature Electrically Controlled Stiffness (ECS) elements and actuators. Using this system, the feeling of the stiffness and forces applied at remote or virtual environments are conceived to be reflected to the users via proportional changes in ERF viscosity. In Figure 8, a graphic presentation is shown of a MEMICA system for the simulation of an Abdominal Aortic Aneurysm surgery. Using such a system the surgeon may be able to conduct a virtual surgery via virtual reality display while "feeling" the stiffness and forces that are involved with the procedure. Once low cost systems are developed remote experts may use such a capability to perform distant inspection or student may perform virtual inspection of aircraft and other structures while being in a classroom.

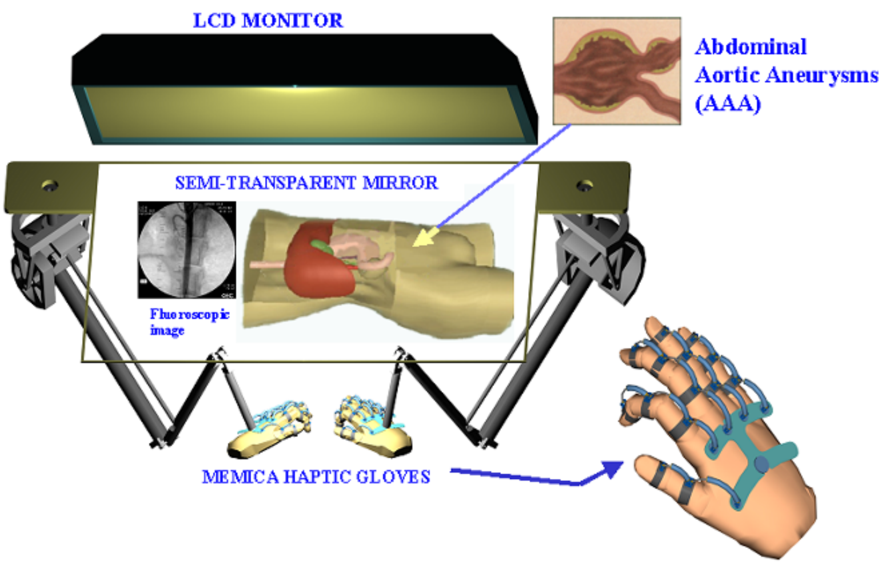

FIGURE 8: Performing virtual reality medical tasks via the Electro-Rheological Fluid based MEMICA haptic interface offers the potential of highly attractive interactive simulation system or remotely operated tasks.

APPLICATION OF BIOLOGICALLY INSPIRED ROBOTS

The evolution in the capabilities that are inspired by biology has increased to a level where more sophisticated and demanding fields, such as space science, are considering the use of such robots. At JPL, a six-legged robot is currently being developed for consideration in future missions to such planets as Mars. Such robots include the LEMUR (Limbed Excursion Mobile Utility Robot). This type of robot would potentially perform mobility in complex terrains, perform sample acquisition and analysis, and many other functions that are attributed to legged animals including grasping and object manipulation. This evolution may potentially lead to the use of life-like robots in future NASA missions that involve landing on various to planets including Mars. The details of such future missions will be designed as a plot, commonly used in entertainment shows rather than conventional mission plans of a rover moving in a terrain and performing simple autonomous tasks. Equipped with multi-functional tools and multiple cameras, the LEMUR robots are intended to inspect and maintain installations beyond humanity's easy reach in space. This spider looking robot also has 6 legs, each of which has interchangeable end-effectors to perform the required mission (see Figure 9). The axis-symmetric layout is a lot like a starfish or octopus, and it has a panning camera system that allows omni-directional movement and manipulation operations.

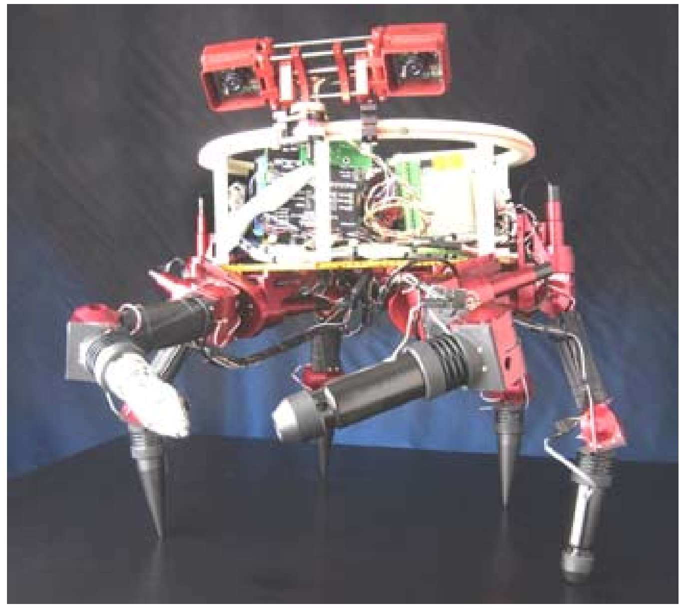

FIGURE 9: The new class of multi-limbed robots called LEMUR (Limbed Excursion Mobile Utility Robot) is under development at JPL [Courtesy of Brett Kennedy, JPL]

SUMMARY AND OUTLOOK

Technologies that allow developing biologically inspired system are increasingly emerging. This includes robots that perform such locomotion techniques as walking, hopping, swimming, diving, crawling, etc. Making robots that are actuated by artificial muscles and controlled by artificial intelligence would create a new reality with great potentials to NDE. One may envision insect-like robots being used to inspect hard to reach areas of aircraft fuselage or engines where the creatures can be launched to conduct the inspection procedures and download the data upon exiting the structure. The emergence of electroactive polymers has enabled potential capabilities that are currently considered science fiction. Using effective EAP actuators to mimic nature would immensely expand the collection and functionality of robots that are currently available. Important addition to this capability can be the application of tele-presence combined with virtual reality using haptic interfaces.

As the technology progresses, it is more realistic to expect that biomimetic robots will become commonplace in our future environment. It will be increasingly difficult to distinguish them from organic creatures, unless intentionally designed to be fanciful. Figure 10 shows an example of a futuristic shark. Sometime in the future, such a robot may be turned into a model of a biomimetic robot by first using computer graphics, and then rapid prototyping of the structures, supported by the biologically inspired capabilities. Such a robot may be used to conduct various NDE tasks including inspection of marine structures. As we are inspired by biology to make more intelligent robotic technology to improve our lives and inspection tools we will increasingly find challenges to such implementations.

FIGURE 10: Photographic view of a real shark that was graphically modified to serve as a model for potential rapid prototyping of future BioRobotic Autonomous UnderSea robotic vehicles [The modified graphics is courtesy of David Hanson, University of Texas, Dallas.]

The author's arm-wrestling challenge having a match between EAP-actuated robots and a human opponent highlights the potential of this technology. Progress towards winning this arm wrestling match will lead to exciting new generations of robots and is expected to benefit NDE in many forms including the development of robots that operate as artificial inspectors.

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