BIOLOGICALLY INSPIRED ROBOTS AS ARTIFICIAL INSPECTORS - SCIENCE FICTION AND ENGINEERING REALITY

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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 and systems were developed to address specific production-line requirements. The emergence of robots has been the result of the need to deal with parts that are too complex to handle by a simple automatic system. The capability to inspect aircraft and large structures has benefited from this evolution in technology where manipulators and crawlers are now commonly used for rapid and reliable scanning both in production line and in the field. Economical factors are continuing to hamper the wide use of robotics for inspection applications however advances in technology are increasingly changing this paradigm. Autonomous robots, which may look like human, can potentially address the need to inspect structures with configuration that are not predetermined. The operation of such robots that mimic biology may take place at harsh or hazardous environments that are too dangerous for human presence. Biomimetic technologies such as artificial intelligence, artificial muscles, artificial vision and numerous others are increasingly becoming common engineering tools. Inspired by science fiction, making biomimetic robots is increasingly becoming an engineering reality and in this paper the state-of-the-art will be reviewed.

Introduction: Human errors have long been recognized as a major factor in the reliability of nondestructive test results. To minimize such errors, there is an increasing reliance on automatic inspection tools that allow faster and consistent tests [Bar-Cohen, 2000]. Crawlers and various manipulation devices are commonly used to perform variety of inspection procedures that include C-scan with contour following capability to rapidly inspect complex structures. In order to operate fast in field conditions and scan large areas, a multifunctional automated crawling system (MACS) was developed at JPL (see Figure 1). This crawler is a novel mobility platform that uses suction cups to adhere to the surface of aircraft structures. MACS was designed to allow integration of board-based NDE instruments for customized scanning tasks. Studying the requirements for such scanners one can soon realize that some tasks can be best performed by machine that emulate human's capability. Making a robot that operate like human is a challenge that currently seems as a science fiction but with the current technology trend such an engineered machine may not be a distant reality.

Developing robots that mimic the shape and performance of biological creatures, i.e. biomimicking, has always been a highly desirable engineering objective. Searching the internet under the keyword robots would identify many links to research and development projects that are involved with robots that are biologically inspired. The entertainment and toy industries have greatly benefited from advances in this technology. Increasingly, robots that are used in movies are operating with realistic behaviour and they even emulate creatures that don't exist anymore (as in the case of dinosaurs in the movie "Jurassic Park"). Visiting toy stores one can easily see how far the technology progressed in making inexpensive toys that imitate biology – such store displays include frogs swimming in a fish bawl and dogs walking back and forth and possibly even barking. Operating robots that emulate the functions and performance of human or animal involve using capabilities of actuators and mechanisms that depend on the state-of-the-art. Upper-end robots and toys are becoming increasingly sophisticated [http://www.designboom.com/eng/education/robot.html] allowing them to walk and talk, where some even operate autonomously and can be remotely reprogrammed to change their characteristic behaviour. Some of the toys or robots can even make expressions and exhibit behaviour that is similar to human and animals. An example of such a robot is the robot Kismet that reacts to human expressions including smiling. As this technology evolves it is becoming more likely to believe that in the future human like robots may be developed as artificial NDE inspectors that operate without human errors, needing no break, not easily distracted and does not get tired. Such robots can perform tasks that are highly reliable and be designed to access very hard to reach areas in a highly repeatable process.

The evolution in robotic capabilities that are inspired by biology has reached the level that sophisticated and demanding tasks can be considered for such fields as space science. At JPL, four and six legged robots are currently being developed for consideration in future missions to such planets as Mars. Such robots include the

LEMUR (Limbed Excursion Mobile Utility Robot), which would potentially perform mobility in complex terrains, acquire samples for analysis, and conduct 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 climbing steep mountains. The details of such future missions may be designed as a plot, commonly used in entertainment shows rather than conventional mission plans of a rover moving in a terrain and performing 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 has legs, each of which has interchangeable end-effectors to perform the required mission (see Figure 2). 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.

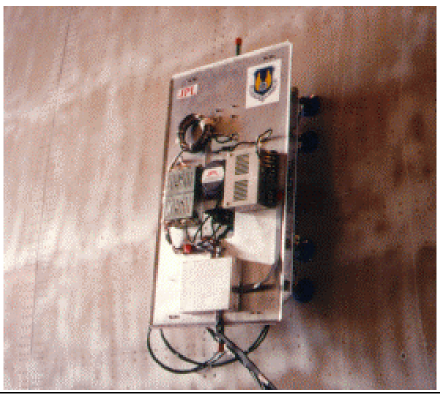

FIGURE 1: MACS crawling on the C-5 aircraft [Bar -Cohen, 2000].

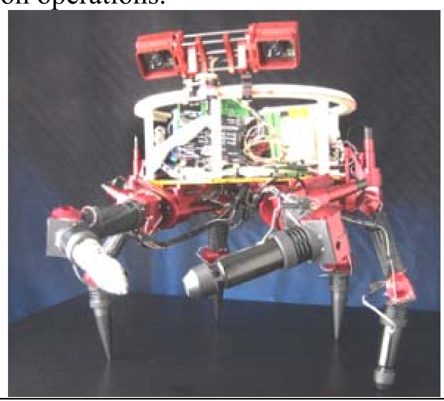

FIGURE 2: A new class of multi-limbed robots called LEMUR (Limbed Excursion Mobile Utility Robot) is under development at JPL [Courtesy of Brett Kennedy, JPL]

In spite of the success in making robots that mimic biology there is still a large gap between the performance of robots and creatures in nature. The required technology is multidisciplinary and has many aspects and one of them is the need for actuators that emulate muscles. The potential for such actuators is increasingly becoming enabled with the emergence of effective electroactive polymers (EAP) [Bar-Cohen, 2001 and 2004]. These materials have functional similarities to biological muscles, including resilience, quiet operation, damage tolerance, and large actuation strains (stretching, contracting or bending), earning them the moniker Artificial Muscle. EAP-based actuators may be used to eliminate the need for gears, bearings, and other components that complicate the construction of robots and are responsible to high costs, weight and premature failures. Visco-elastic EAP materials can potentially provide more lifelike aesthetics, vibration and shock dampening, and more flexible actuator configurations. 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.

The capability of EAPs to emulate muscles offers robotic capabilities that have been in the realm of science fiction when relying on existing actuators. The large displacement that can be obtained using low mass, low power and, in some of the EAPs, also low voltage, makes them attractive actuators. As an example of an application, at JPL EAP actuators that can induce bending and longitudinal strains 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 and it was made to grab rocks similar to human hand.

In recognition of the need for international cooperation among the developers, users, and potential sponsors, the author organized the first EAP Conference on March 1-2, 1999, through SPIE [Bar-Cohen, 1999]. This conference was the largest ever on this subject, marking an important milestone and turning the spotlight onto these emerging materials and their potential. This SPIE conference is now organized annually and has been steadily growing in number of presentations and attendees. Currently, there is a website that archives related information and links to homepages of EAP research and development facilities worldwide [http://eap.jpl.nasa.gov], and a semi-annual Newsletter is issued electronically [http://ndeaa.jpl.nasa.gov/nasa-nde/lommas/eap/WW-EAP-Newsletter.html]. Further, the author edited and co-authored a reference book on EAP that has been published in 2001 [Bar-Cohen, 2001] with its 2nd edition was published in March 2004 [Bar-Cohen, 2004]. This book provides a comprehensive documented reference, technology user's guide, and tutorial resource, with a vision for the future direction of this field. It covers the field of EAP from all its key aspects, i.e., its full infrastructure, including the available materials, analytical models, processing techniques, and characterization methods [http://ndeaa.jpl.nasa.gov/nasa-nde/yosi/yosi-books.htm].

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 a 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 seeing a handicapped person jogging to the grocery store using this technology. The increased resources, the growing number of investigators conducting research related to EAP, and the improved collaboration among developers, users, and sponsors are already leading to rapid progress in this.

One such commercial product has already emerged in Dec. 2002 is a form of a Fish-Robot (Eamex, Japan). An example of this Fish-Robot is shown in Figure 5. It swims without batteries or a motor and it uses EAP materials that simply bend upon stimulation. For power it uses inductive coils that are energized from the top and bottom of the fish tank. This fish represents a major milestone for the field, as it is the first reported commercial product to use electroactive polymer actuators. Further, recent advances in understanding the behaviour of EAP materials and the improvement of their efficiency led to the point that the first armwrestling competition is planned for March 7, 2005 during the EAPAD Conference where three organizations (listed by order of announcement) have already stated their readiness for this competition: (a) SRI International, Menlo Park, CA, USA (Currently seeking the necessary funds to develop the required arm in order to compete); (2) Environmental Robots Incorporated (ERI), Albuquerque, New Mexico, USA (see Figure 6); and (3) Swiss Federal Laboratories for Materials Testing and Research, EMPA, Dubendorf, Switzerland.

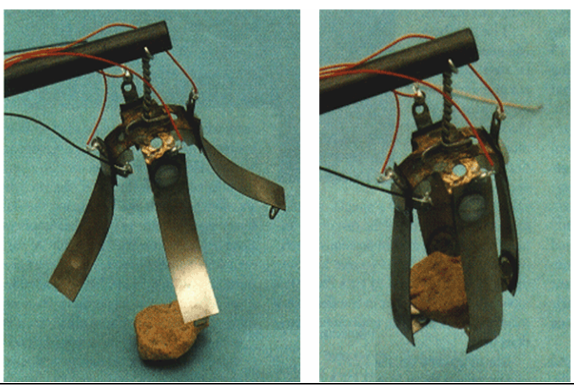

FIGURE 3: 4-finger EAP gripper lifting a rock.

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

FIGURE 5: The first commercial EAP product

FIGURE 6: One of the three EAP wrestling arms that

- a fish robot (courtesy of Eamex, Japan).	were developed to compete against a human opponent. (Courtesy of M. Shahinpoor, ERI, New Mexico, USA)

Historical review and currently available active polymers: 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, investigators started to examine other polymer systems, and a series of effective materials have emerged [http://www.ndt.net/article/yosi/yosi.htm]. 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].

EAP can be divided into two major categories based on their activation mechanism including ionic and electronic (Table 1). The electronic EAP, such as electrostrictive, electrostatic, piezoelectric, and ferroelectric, are driven by Coulomb forces. This type of EAP materials can be made to hold the induced displacement while activated under a DC voltage, allowing them to be considered for robotic applications. These materials have a greater mechanical energy density and they can be operated in air with no major constraints. However, the electronic EAP require a high activation fields (>30-V/μm) that may be close to the breakdown level. In contrast to the electronic EAP, ionic EAP are materials that involve mobility or diffusion of ions and they consist of two electrodes and an electrolyte. The activation of the ionic EAP can be made by as low as 1-2 Volts and mostly a bending displacement is induced. Examples of ionic EAP include gels, polymer-metal composites, conductive polymers, and carbon nanotubes. Their disadvantages are the need to maintain wetness and they pose difficulties to sustain constant displacement under activation of a DC voltage (except for conductive polymers).

TABLE 1: List of the leading EAP materials

Electronic EAP	**Ionic EAP**
Dielectric EAP	• Carbon Nanotubes (CNT)
Electrostrictive Graft Elastomers	• Conductive Polymers (CP) (see Figure 7)
Electrostrictive Paper	• ElectroRheological Fluids (ERF)
Electro-Viscoelastic Elastomers	• Ionic Polymer Gels (IPG)
Ferroelectric Polymers	• Ionic Polymer Metallic Composite (IPMC)
Liquid Crystal Elastomers (LCE)	

The induced displacement of both the electronic and ionic (see example in Figure 7) EAP can be designed geometrically to bend, stretch or contract. Any of the existing EAP materials can be made to bend with a significant bending response, offering an actuator with an easy to see reaction. However, bending actuators have relatively limited applications due to the low force or torque that can be induced. One important question, which has been asked by new users or researchers/engineers who are comers to this field, is: "where can I get these materials?" This issue of unavailability of commercial EAP materials is dampening the rate of progress in the field of EAP. To help potential users, the author has established a website to provide "recipes" describing how to make the various EAP materials [http://ndeaa.jpl.nasa.gov/nasa-nde/lommas/eap/EAP-recipe.htm]. To help further, the author compiled inputs from companies that make EAP materials, prototype devices or provide EAP related processes and services. The inputs were compiled into a handy table that is posted on one of the links of the WW-EAP webhub: http://ndeaa.jpl.nasa.gov/nasa-nde/lommas/eap/EAP-material-n-products.htm

FIGURE 7: Conductive EAP actuator is shown bending under stimulation of 2-V, 50-A.

Need for EAP technology infrastructure: 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 [Bar-Cohen, 2001 and 2004]. Effectively addressing the requirements of the EAP infrastructure involves developing adequate understanding of EAP materials' behaviour, as well as processing and characterization techniques.

Enhancement of the actuation force requires understanding the basic principles using computational chemistry models, comprehensive material science, electro-mechanics analytical tools and improved material processing techniques. Currently, efforts are underway to gain a better understanding of the parameters that control the EAP electro-activation force and deformation. The processes of synthesizing, fabricating, electroding, shaping and handling are needed to be refined to maximize the EAP materials actuation capability and robustness. Methods of reliably characterizing the response of these materials are required to establish database with documented material properties in order to support design engineers considering use of these materials and towards making EAP as actuators of choice. Various configurations of EAP actuators and sensors will need to be studied and modelled to produce an arsenal of effective smart EAP driven system. In the last six years, significant international effort has been made to address the various aspects of the EAP infrastructure and to tackle the multidisciplinary issues [Bar-Cohen, 2001]. Numerous researchers and engineers are now addressing the infrastructure related issues as being reported in the conference proceedings of the SPIE and MRS conferences on this subject [http://eap.jpl.nasa.gov]. The author believes that an emergence of a niche application that addresses a critical need will significantly accelerate the transition of EAP from novelty to actuators of choice. In such case, the uniqueness of these materials will be exploited and commercial product will emerge in spite of the current limitations of EAP materials.

Making robots actuated by EAP: Mimicking nature would immensely expand the collection and functionality of 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. To promote the development of effective EAP actuators, which could impact future robotics, toys and animatronics, two test-bed platforms were developed (see Figure 8). These platforms are available at the author's NDEAA Lab at JPL and they include an Android head 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 modelled 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 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 growing availability of EAP materials that exhibit high actuation displacements and forces is opening new avenues to bioengineering in terms of medical devices and assistance to humans in overcoming different forms of disability. Areas that are being considered include an angioplasty steering mechanism, and rehabilitation robotics. For the latter, exoskeleton structures are being considered in support of rehabilitation or to augment the mobility and functionalities of patients with weak muscles. .

Designing sociable robots: Robots are increasingly making their way into human environments where they are not restricted to the factory floor or by local hazards. This progress is now leading to a new paradigm of interaction between humans and robots, where robot are behaving as sociable partner rather than a tool. As such, robots are being developed to communicate with, cooperate with, and learn from people in familiar human-oriented terms. This poses new challenges and motivates new entertainment, educational, and health related applications for robots that play a part in our daily lives.

FIGURE 8: An android head and a robotic hand that are serving as platforms for the development of artificial muscles [This photo was made at JPL where the head was sculptured and instrumented by D. Hanson, University of Texas, Dallas. The hand was made by G. Whiteley, Sheffield Hallam U., UK.]

This trend is supported by numerous experimental findings in the field of human computer interaction and human robot interaction. These studies have shown that people bring to bear a wide range of social rules and learned behaviours that guide their interactions with, and attitudes toward, interactive technologies. Generally, the social and emotional reactions that people have towards such systems are important keys to building more useful, successful, and productive technologies. Robots that participate in rich human-style social exchange with people offer a number of advantages. For instance, communicating with them would not require any additional training since humans are already experts in social interaction. Also, if the robot could engage in various forms of social learning (imitation, emulation, tutelage, etc.), it would be easier for people to teach robots new tasks. Advances at MIT in building an anthropomorphic robot, led to the development of the robot head Kismet, which can engage people in expressive social interaction. Kismet is designed to enter into natural and intuitive social interaction with a person, reminiscent of adult-infant exchanges. It perceives a variety of natural social cues from visual and auditory channels, and delivers social signals to people through gaze direction, facial expression, body posture, and vocalizations. Further information about this robot expressivity and videos showing it making expressions can be seen on the Robotic Life Group of MIT [http://web.media.mit.edu/~cynthiab/NewFiles/research.html].

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 in Bar-Cohen and Breazeal, 2003]. To address this need, the engineering community is developing haptic (tactile and force) feedback systems allowing users to immerse themselves in the display medium while being connected thru haptic and tactile interfaces to allow them to perform telepresence and "feel" at the level of their fingers and toes. 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 that are active on demand. 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.

Summary and outlook: Technologies that allow developing biologically inspired system are increasingly emerging. These technologies are allowing development of robots that can perform combinations of locomotion techniques including walking, hopping, swimming, diving, crawling, flying, etc. with selectable behaviour and performance characteristics. Making robots that are actuated by electroactive polymers, namely artificial muscles that are controlled by artificial intelligence would create a new reality with great potentials to NDE. Electroactive polymers have emerged with great potential enabling the development of unique biologically inspired devices. As artificial muscles, they are offering capabilities that are currently considered science fiction. Enhancement of the performance of EAP will require advances in related computational chemistry models, comprehensive material science, electro-mechanics analytical tools, and improved material processing techniques. 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 that employ the ERF-based MEMICA system. While such capabilities are expected to significantly change future robots, additional effort is needed to develop robust and effective EAP-based actuators.

In addition to developing better actuators, a discipline of visco-elastic engineering and control strategies will need to be developed to supplant the traditional engineering of rigid structures. There are still many challenges, but the recent trend of international cooperation, the greater visibility of the field and the surge in funding of related research projects are offering great hope. To assist in the development of effective biologically inspired robots, an Android head and robotic hand were made available to the author to offer them as platforms for the demonstration of internationally developed actuators. 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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