Biomimetic Robots using EAP as Artificial Muscles – Progress and Challenges

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ABSTRACT

Biology offers a great model for emulation in areas ranging from tools, computational algorithms, materials science, mechanisms and information technology. In recent years, the field of biomimetics, namely mimicking biology, has blossomed with significant advances enabling the reverse engineering of many animals' functions and the implementation of some of these capabilities. An indication of this progress can be seen at many toy stores, where increasingly toys appear and behave like living creatures including dogs, cats, birds, frogs and others. Other benefits of this technology include prosthetic implants and human aiding mechanisms that may be interfaced with the human brain to assist in hearing or seeing. Technology evolution led to such fields as artificial intelligence and artificial muscles, which allow the consideration of making more realistic biomimetic intelligent robots. Actuation via polymers that exhibit large displacement in response to other than electrical signal (e.g., chemical, thermal and light) was feasible for many years. However, initially electroactive polymers (EAP) received relatively little attention due to their limited actuation capability. Progress in the last fifteen years led to dramatic advances in the capability of these materials. Currently, efforts are underway to address the many challenges that are hampering the practical application of these materials. Various novel mechanisms and devices were already demonstrated including robot fish, catheter steering element, robotic arm, gripper, loudspeaker, active diaphragm, and dust-wiper. Other applications that are currently being considered include active Braille display for blind people and electroactive clothing, e.g., smart-bra with battery driven shape control. This paper will review the state of the art and challenges to biologically-inspired technologies and the role that EAP is expected to play as the technology evolves.

INTRODUCTION

In recent years, significant advances have been made in robotics, artificial intelligence and others fields allowing the development of sophisticate biomimetic devices and robots [Bar-Cohen and Breazeal, 2003; and Bar-Cohen, 2004a]. Scientists and engineers are reverse engineering many of animals' performance characteristics using these advances. This interdisciplinary work has resulted in machines that can recognize facial expressions, understand speech, and perform locomotion in robust bipedal gaits similar to humans. More recently, advances in polymer sciences have resulted in artificial muscles based on EAP materials that show functional characteristics remarkably similar to biological muscles [Bar-Cohen, 2001 and 2004. The accelerating pace of the advancements in the field of biomimetics seems to make evident that the emergence of machines as our peers is imminent. Although this topic brings with it enormous implications including but not limited to questions regarding the nature of evolution and its role in technological progression. The technology is greatly benefited from such fields as Psychology of Biomimetic Robots, Integrative Biology, Biomimetic Animated Creatures, Artificial Life, Functionality Elements of Biomimetic Robots, and applications for Biologically Inspired Intelligent Robotics.

Generally, with today's technology one can quite well graphically animate the appearance and behavior of biological creatures. However, in past years, engineering such biomimetic intelligent creatures as realistic robots was a significant challenge due to the physical and technological constraints and shortcomings of existing technology. Making such robots that can hop and land safely without risking damage to the mechanism, or making body and facial expression of joy and excitement are very easy tasks for human and animals to do but extremely complex to engineer. The use of artificial intelligence, effective artificial muscles and other biomimetic technologies are expected to make the possibility of realistically looking and behaving robots into more practical engineering models.

Making biologically inspired intelligent robots requires understanding the biological models as well as advancements in analytical modeling, graphic simulation and the physical implementation of the related technology. The research and engineering areas that are involved with the development of biologically-inspired intelligent robots are multidisciplinary and they include materials, actuators, sensors, structures, functionality, control, intelligence and autonomy. While the engineering challenges are very interesting to address there are also fundamental issues that need attention. Some of these issues include self-defense, controlled-termination as well as many others. There is already extensive heritage of making robots and toys that look and operate similar to biological creatures and models for such robots are greatly inspired by science fiction (books, movies, toys, animatronics, etc.). These models have created perceptions and expectations that are far beyond the reach of current engineering capabilities, which are constrained by laws of physics and current state-of-the-art.

EAP actuated robotic mechanisms are enabling engineers to create devices that were previously only imaginable in science fiction. 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 1. 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.

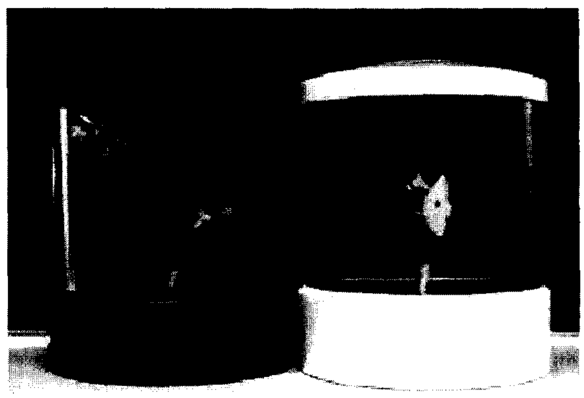

FIGURE 1: The first commercial EAP product - a fish robot (courtesy of Eamex, Japan)

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 and tongs. 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. 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.

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.

EAP AS 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 are also known as artificial muscles [Bar-Cohen, 2001 and 2004]. 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 can be used to make mechanical devices and robots with no traditional components like gears, and bearings, which are responsible to their high costs, weight and premature failures.

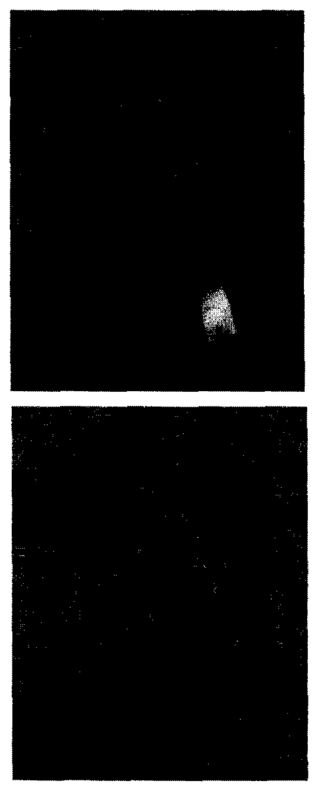

FIGURE 2: 4-finger EAP gripper lifting a rock.

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 perform expressivity. As an example of an application, at the Jet Propulsion Lab (JPL) EAP actuators were used to design and construct a miniature robotic arm (see Figure 2). This robotic arm illustrates some of the unique capabilities of EAP, where its gripper consists of four fingers in the form of IPMC (Ionic polymer metal composite) strips with hooks at the bottom emulating fingernails. This arm was made to grab rocks similar to human hand.

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, in an effort to promote worldwide development towards the realization of the potential of EAP materials the author posed an armwrestling challenge. A graphic rendering of this challenge is illustrated in Figure 3. In posing this challenge, the author sought to see an EAP activated robotic arm win against human in a wrestling match to establish a baseline for the implementation of the advances in the development of these materials. Success in wrestling against human will enable capabilities that are currently considered impossible. It would allow applying EAP materials to improve many aspects of our life where some of the possibilities include effective implants and prosthetics, active clothing, realistic biologically inspired robots as well as fabricating products with unmatched capabilities and dexterity. Recent advances in understanding the behavior of EAP materials and the improvement of their efficiency led to the point where the possibility of EAP actuated arm can win such wrestling match may become feasible in the coming years. The most notable milestone is the recent announcement of scientists from SRI International, USA, stating that they believe they can build such a robotic arm. To plan the first international arm-wrestling competition efforts are currently underway to consider holding the competition as part of one of the SPIE's Annual International EAPAD (EAP Actuators and Devices) Conferences in San Diego, California, USA. 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 see one day a handicapped person jogging to the grocery store using this technology.

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 The International Society for Optical Engineering (SPIE) as part of the Smart Structures and Materials Symposium [Bar-Cohen, 1999]. This conference was held in Newport Beach, California, USA, and was the largest ever on this subject, marking an important milestone. This conference turned the spotlight onto these emerging materials and their potential. Following this success, a Materials Research Society (MRS) conference was initiated to address fundamental issues related to the material science of EAP [Zhang et al., 1999]. In recent years, there has been increasing number of organizations and technical societies who are organizing workshops, meetings and conferences with sessions on EAP. The SPIE's EAPAD conferences are now organized annually and have been steadily growing in number of presentations and attendees. In addition to the conferences, there is a website called the WorldWide EAP (WW-EAP) Webhub that archives related information and links to homepages of EAP research and development facilities worldwide [http://ndeaa.jpl.nasa.gov/nasa-nde/lommas/eap/EAP-web.htm]. Since June 1999, the semi-annual WW-EAP Newsletter has been published with short synopses from authors worldwide providing a snapshot of their advances. This Newsletter is published electronically and its issues are accessible via the above mentioned WW-EAP webhub [http://ndeaa.jpl.nasa.gov/nasa-nde/lommas/eap/WW-EAP-Newsletter.html]. Further, the author edited a reference book on EAP that has been published in 2001 [Bar-Cohen, 2001] with its 2nd edition is expected to be published before the 2004 EAPAD Conference [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.

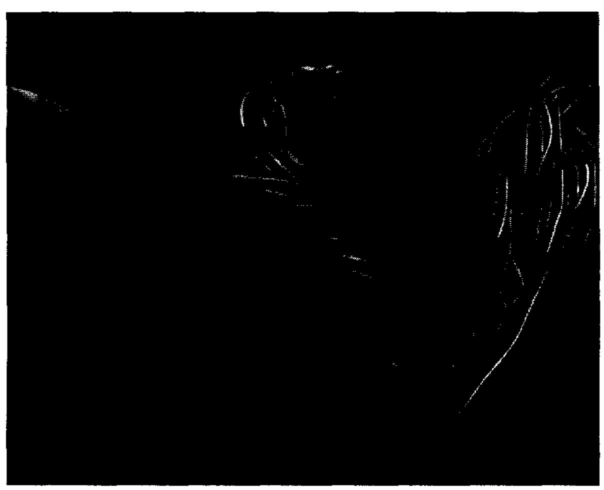

FIGURE 3: Grand challenge for the development of EAP actuated robotics.

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. The challenges to making such robots can be seen in Figure 4 where human-like and dog-like robots are shown to hop and express joy. Both tasks are easy for human and dogs to do but are extremely complex to incorporate into robots.

To promote the development of effective EAP actuators, which could impact future robotics, toys and animatronics, two test-bed platforms were developed (see Figure 5). These platforms are available at the Principal author's 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 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 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. 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 EAPs. The address of this website is: 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 4: A vision of joyfully hopping human-like and dog-like robots actuated by EAP materials (right). **ACKNOWLEDGEMENT**: The human-like graphics was created by Robert M. Brown, JPL, where Zensheu Chang, JPL, was photographed hopping and smiling, whereas the eyes and nose of Jill Bonneville, JPL, were superimposed onto the face. The dog graphics is the contribution of David Hanson, U. of Texas, Dallas. This graphics was modified by Robert M. Brown, JPL.

FIGURE 5: An android head and a robotic hand that are serving as biomimetic platforms for the development of artificial muscles

ACKNOWLEDGEMENT: 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.

The field of artificial muscles offers many important capabilities for the engineering of robots that are inspired by biological models and systems. The easy capability to produce EAP in various shapes and configurations can be exploited using such methods as stereolithography and ink-jet processing techniques. Potentially, a polymer can be dissolved in a volatile solvent and ejected drop-by-drop onto various substrates. Such rapid prototyping processing methods may lead to mass-produced robots in full 3D details including the actuators allowing rapid prototyping and quick transition from concept to full production [Chapter 14 at Bar-Cohen, 2001]. A possible vision for such technology might be the fabrication of insect-like robots that can be made to fly and pack themselves into the packaging box to be ready for shipping once they are made. Other example can be the use of a movie script to produce the needed robots, which can be modified rapidly with an evolving script. Biologically inspired robots may be developed with capabilities that are far superior to natural creatures since they are not constrained by evolution and survival needs. Examples may include artificial bugs that may walk on water, swim, hop, crawl and walk while reconfigure themselves as needed when required. Important addition to this capability can be the application of telepresence combined with virtual reality using haptic interfaces. While such capabilities are expected to significantly change future robots, additional effort is needed to develop robust and effective polymer-based actuators.

DESIGNING SOCIABLE ROBOTS

Robots are increasingly making their way into human environments where they are no restricted to the factory floor or hazardous locales. This progress is now leading to a new paradigm of interaction between humans and robots, where robot as 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 domestic, entertainment, educational, and health related applications for robots that play a part in our daily lives.

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 behaviors 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.

PRACTICAL 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, four and six legged robot are 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. 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 has 6 legs, each of which has interchangeable end-effectors to perform the required mission (see Figure 7). 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.

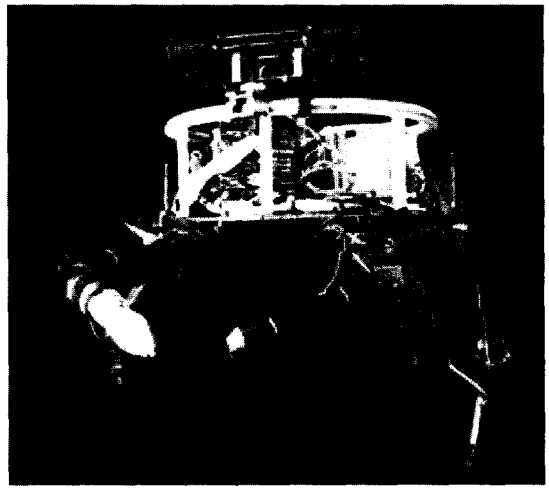

FIGURE 7: A new class of multi-limbed robots called LEMUR (Limbed Excursion Mobile Utility Robot) is under development at JPL [Courtesy of Brett Kennedy, JPL]

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 enable engineering reality that used to be considered science fiction. 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. 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. 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. The Principal author's arm-wrestling challenge having a match between EAP-actuated robots and a human opponent highlights the potential of this technology.

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REFERENCES

Bar-Cohen Y. (Ed.), "Automation, Miniature Robotics and Sensors for Nondestructive Evaluation and Testing," Volume 4 of the Topics on NDE (TONE) Series, American Society for Nondestructive Testing, Columbus, OH, ISBN 1-57117-043 (2000), pp.1-481.

Bar-Cohen Y. (Ed.), *Biomimetics - Biologically-Inspired Technologies*, CRC Press, in preparation (expected to be published in Dec. 2004a).

Bar-Cohen Y. (Ed.), *Electroactive Polymer (EAP) Actuators as Artificial Muscles - Reality, Potential and Challenges*, ISBN 0-8194-4054-X, SPIE Press, Vol. PM98, (March 2001), pp. 1-671. http://ndeaa.jpl.nasa.gov/nasa-nde/yosi/yosi-books.htm

Bar-Cohen Y. (Ed.), ibid, 2nd Edition Volume PM136, (to be published, March 2004)

Bar-Cohen Y., and C. Breazeal (Eds), "Biologically-Inspired Intelligent Robots," SPIE Press, Vol. PM122, ISBN 0-8194-4872-9 (May 2003), pp. 1-393.

Bar-Cohen, Y., (Ed.), Proceedings of the Electroactive Polymer Actuators and Devices, Smart Structures and Materials 1999, SPIE Proc. Vol. 3669, (1999), pp. 1-414.

Breazeal C., *Designing Sociable Robots*, MIT Press (2002). http://www.media.mit.edu/~cynthiab/

Eguchi M., "On the Permanent Electret," Philosophical Magazine, Vol. 49 (1925) pp 178.

Katchalsky, A., "Rapid Swelling and Deswelling of Reversible Gels of Polymeric Acids by Ionization", Experientia, Vol. V, (1949), pp 319-320.

Kornbluh R. and R. Pelrine, "Application of Dielectric EAP Actuators," Chapter 16 in [Bar-Cohen, 2001a], pp. 457-495.

Roentgen, W.C. , "About the changes in shape and volume of dielectrics caused by electricity," Section III in G. Wiedemann (Ed.), *Annual Physics and Chemistry Series,* Vol. 11, John Ambrosius Barth Publisher, Leipzig, German (1880) pp. 771-786,.(In German)

Sacerdote M. P. "On the electrical deformation of isotropic dielectric solids," *J. Physics*, 3 Series, t, VIII, 31 (1899), 282-285. (In French)

Zhang Q. M., T. Furukawa, Y. Bar-Cohen, and J. Scheinbeim, Eds., Proceedings of the Fall MRS Symposium on electroactive polymers (EAP), Vol. 600, Warrendale, PA, (1999) pp. 1-336.