

Electro-active polymers: current capabilities and challenges

Yoseph Bar-Cohen

Jet Propulsion Laboratory/Caltech

4800 Oak Grove Drive, M/S 82-105, Pasadena, CA 91109, USA

e-mail: yosi@jpl.nasa.gov Web: <http://ndea.jpl.nasa.gov>

ABSTRACT

In the last ten years, new EAP materials have emerged that exhibit large displacement in response to electrical stimulation enabling great potential for the field. To develop efficient and robust EAP material for practical applications efforts are underway to understand the behavior of EAP materials and improved characterization techniques. Further, to enhance the actuation force the basic principles are being studied using comprehensive material science, electro-mechanics analytical tools and improved material processing techniques to gain better understanding of the parameters that control the EAP electro-activation force and deformation. The processes of synthesizing, fabricating, electroding, shaping and handling are being 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 need to be studied and modeled to produce an arsenal of effective smart EAP driven system. The development of the infrastructure is a multidisciplinary task involving materials science, chemistry, electro-mechanics, computers, electronics, and others. This paper will be a review of the status of the EAP field and the challenges to practical application of EAP materials as actuators.

Keywords: EAP, robotics, biomimetics, biologically inspired robots

1. INTRODUCTION

The fact that certain types of polymers can change shape in response to electrical stimulation has been known for decades however the induced strain was relatively small. Since the early 90s, electroactive polymers (EAP) have emerged that can be stimulated to produce a significant shape or size change. The behavior similarity of these materials to biological muscles acquired them the moniker "artificial muscles" [Bar-Cohen, 2001a]. The large induced displacement capability of these new EAP materials is attracting the attention of engineers and scientists from many different disciplines. Practitioners in biomimetics, a field where robotic mechanisms are developed based on biologically inspired models, are particularly excited about these materials since they can be applied to mimic the movements of animals and insects. The low robustness of the current EAP materials are still limiting their applications. In recognition of the need for international cooperation among the developers, users, and potential sponsors, the author has initiated and organized the annual SPIE Conferences on EAP [Bar-Cohen, 1999]. This conference was followed with the organization of the MRS conference on EAP [Zhang, et al, 1999] Further, a website was formed with links to homepages of EAP research and development facilities worldwide (<http://ndea.jpl.nasa.gov/nasa-nde/lommas/eap/EAP-web.htm>), and a semi-annual Newsletter is being issued electronically (<http://ndea.jpl.nasa.gov/nasa-nde/lommas/eap/WW-EAP-Newsletter.html>). The increased resources, the growing number of investigators conducting research related to EAP, and the improved collaboration among developers, users, and sponsors has to lead to a significant advancement in this field. To highlight the potential of this field, in 1999, the author posted a challenge to the worldwide community of EAP experts to develop a robotic arm that is actuated by artificial muscles to win an arm wrestling match with a human opponent. Progress towards this goal will lead to great benefits, particularly in the medical field, 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. As advances are made in this field of EAP it is interesting examine the progress that was reported so far and assess the challenges that are facing this field. This paper examines the state of the art of EAP as potential actuators and devices.

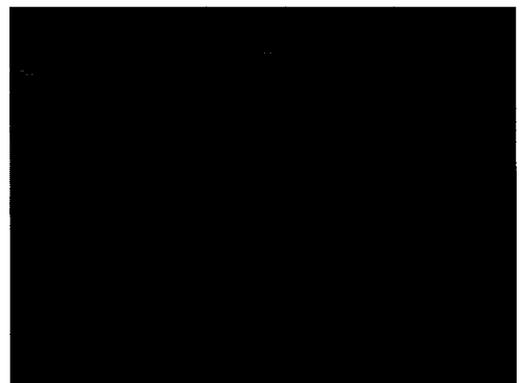


FIGURE 7: Grand challenge for the development of EAP actuated robotics.

2. 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, 2001a].

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 et al, 2001].

EAP can be divided into two major categories based on their activation mechanism including ionic and electronic (Table 1). Coulomb forces drive the electronic EAP, which include electrostrictive, electrostatic, piezoelectric and ferroelectric. 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 EAP 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 ($>100\text{-V}/\mu\text{m}$) that may be close to the breakdown level. In contrast to the electronic EAP, ionic EAPs are materials that involve mobility or diffusion of ions and they consist of two electrodes and 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
<ul style="list-style-type: none"> • Dielectric EAP • Electrostrictive Graft Elastomers • Electrostrictive Paper • Electro-Viscoelastic Elastomers • Ferroelectric Polymers • Liquid Crystal Elastomers (LCE) 	<ul style="list-style-type: none"> • Carbon Nanotubes (CNT) • Conductive Polymers (CP) (see Figure 1) • ElectroRheological Fluids (ERF) • Ionic Polymer Gels (IPG) • Ionic Polymer Metallic Composite (IPMC)

The induced displacement of both the electronic and ionic 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 (see example in Figure 1). However, bending actuators have relatively limited applications due to the low force or torque that can be induced. EAP materials are still custom made mostly by researchers and they are not available commercially. To help in making them widely available, the author established a website that provides fabrication procedures for the leading types of EAP materials. The address of this website is:

<http://ndea.jpl.nasa.gov/nasa-nde/lommas/eap/EAP-recipe.htm>

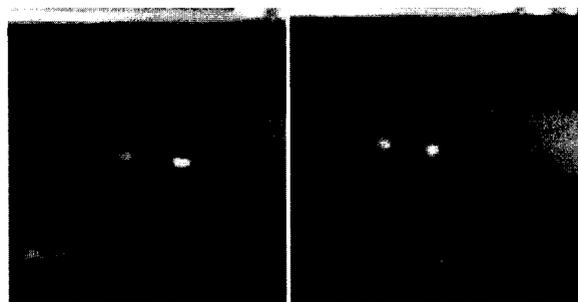


FIGURE 1: Conductive EAP actuator is shown bending under stimulation of 2-V, 50-A.

3. 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 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 for an established infrastructure [Bar-Cohen, 2001a] and significant effort is underway including studies to understand the materials' behavior, as well as the development of effective 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 [Chapter 14, Bar-Cohen, 2001a]. Efforts are made 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 being refined to maximize the EAP materials actuation capability and robustness. Various configurations of EAP actuators and sensors are being studied and modeled to produce an arsenal of effective smart EAP driven system. Methods of reliably characterizing the response of these materials are being developed towards establishing database with documented material properties in order to support design engineers that are considering use of these materials and making EAP as actuators of choice.

In the last three years, significant international effort has been made to address the various aspects of the EAP infrastructure and to tackle the multidisciplinary issues [Bar-Cohen, 2001a]. Numerous researchers and engineers are now addressing each element of the field infrastructure as can be viewed in the conference proceedings of the SPIE and MRS conferences on this subject [Bar-Cohen, 1999, 2000 and 2001b; Zhang, 1999]. 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.

4. BIOLOGICALLY INSPIRED

Making robots that mimic the operation and appearance of human and/or animals is a challenge that seems to be a science fiction but, with the current trend, this may not be a too distant reality. This objective of mimicking creatures, also known as biomimetics, has always been highly desirable by the engineering community. Searching the internet under the keyword "robots" would identify many links to research and development projects that are involved with robots having features that are biologically inspired. The entertainment and toy industries are continually benefiting from the advancements in this technology. Increasingly, robots are used in movies showing creatures with realistic behavior even if they don't exist anymore, as in the case of dinosaurs in the movie "Jurassic Park," or never existed such as "ET". Visiting toy stores one can easily see how far the technology progressed in making toys that imitate biology – such store displays include frogs swimming in a fish bowl and dogs walking back and forth and possibly even barking. Operating robots that emulate the functions and performance of human (Figure 2) or animals involve using capabilities of actuators and mechanisms that are critically dependent on the state-of-the-art. Upper-end robots and toys are becoming increasingly sophisticated allowing them to walk and talk, including some that can be operated autonomously as well as remotely reprogrammed to change their characteristic behavior (see Figure 3 and 4). Some of the toys or robots can even make expressions and exhibit behavior that is similar to human and animals. An example of such a robot is shown in Figure 5 where the robot Kismet reacts to human expressions including smiling. As this technology evolves it is becoming more likely to believe that future human-like robots may be developed to perform tasks, which require high reliability at hazardous locations without having human faults of losing attention when the task is redundant, needing a break, being distracted or getting tired.

In spite of the success in making robots that mimic biology there is still a wide gap between the performance of robots and nature creatures. The required technology is multidisciplinary and has many aspects including the need for EAP actuators as artificial emulate



FIGURE 2: Biomimetic robot [Bar-Cohen, 2002] (Graphics is courtesy of David Hanson, UTD)

muscles benefiting from the functional similarities, including resilience, damage tolerance, and large actuation strains (stretching, contracting or bending). 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 EAP may enable even the movement of the covering skin to define the character of the robots and provide expressivity.

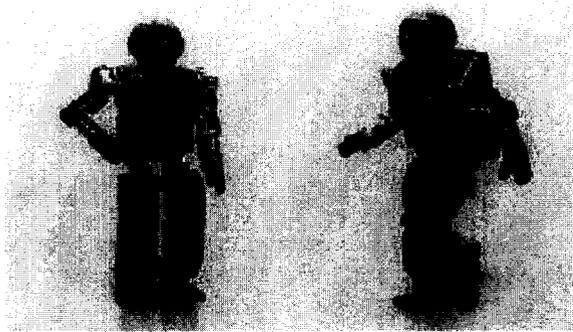


FIGURE 3: Sony's SDR3 is an example of a robot that can perform functions that emulate human
[\[http://www.designboom.com/eng/education/robot.html\]](http://www.designboom.com/eng/education/robot.html)

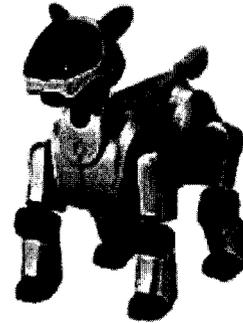


FIGURE 4: Sony's AIBO - Sony 2nd Generation ERS-210 is a sophisticated pet-like robot
[\[http://www.us.aibo.com/ers_210/product.php?cat=aibo\]](http://www.us.aibo.com/ers_210/product.php?cat=aibo)

FIGURE 5: The robot, Kismet, responds to human expressions from Cynthia Breazeal, MIT [courtesy of MIT Press Office
[http://www.ai.mit.edu/people/cynthia/cynthia.html\]](http://www.ai.mit.edu/people/cynthia/cynthia.html)



The capability of EAPs to emulate muscles offers robotic capabilities that are still 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 6). 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.

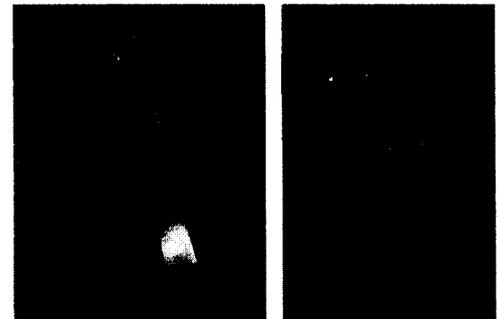


FIGURE 6: 4-finger EAP gripper lifting a rock.

5. 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 [Chapters 17 to 21 in Bar-Cohen 2001a]. Such robots can be programmed to take on performing procedures that include NDE and many other complex ones. The challenges to making such a robot are portrayed in Figure 2 where the vision for such robots is shown in the form of human-like that hops and strongly expresses joy. Both tasks are easy for human to do but are extremely complex to perform by an existing robots.

To promote the development of effective EAP actuators, which could impact the future of robotics, toy industry, animatronics and others, two platforms were developed and are now available at the Jet Propulsion Laboratory (JPL). These

platforms include an Android head, which can make facial expressions [see Figure 7 or video showing the Android expressivity on <http://ndeaa.jpl.nasa.gov/nasa-nde/lommas/eap/EAP-web.htm>], and a robotic hand with activatable joints [Figure 8, and video on <http://ndeaa.jpl.nasa.gov/nasa-nde/lommas/eap/EAP-web.htm>]. 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 serve as a baseline and they would be substituted by EAP when such materials are developed as effective actuators.

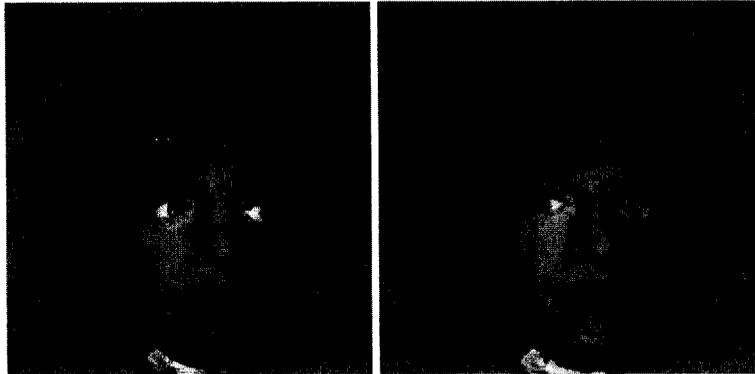


FIGURE 7: An android head (Photographed at JPL) as EAP platform will use such actuators to make facial expressions (Courtesy of G. Pioggia, University of Pisa, Italy).

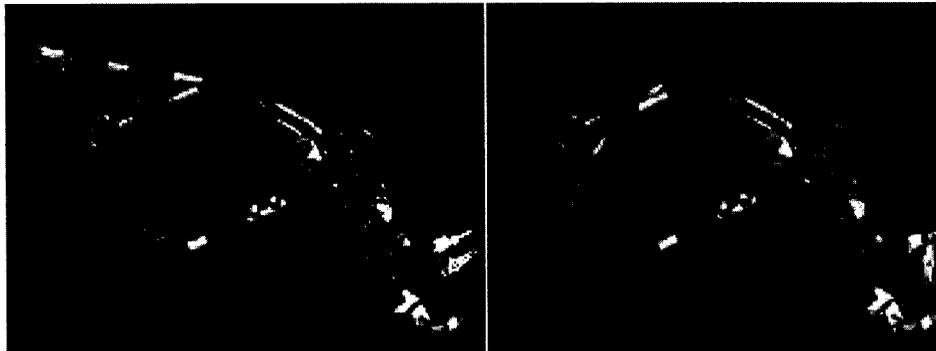


FIGURE 8: Robotic hand (Photographed at JPL) is available at JPL as a platform for demonstration of EAP actuators [Courtesy of Dr. Graham Whiteley, Sheffield Hallam U., UK. The actuators were installed by Giovanni Pioggia – University of Pisa, Italy/JPL].

The ease 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, 2001a]. Making insect-like robots could help for example to inspection hard to reach areas of aircraft structures where the creatures can be launched to conduct the inspection procedure and download the data upon exiting the structure.

6. 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 tele-presence capabilities. To address this need, the engineering community has started developing haptic (tactile and force) feedback systems. Users of future simulators may immerse themselves into the display medium while being connected thru haptic and tactile interfaces to allow them to “feel the action” at the level of their fingers and toes. Thus, an expert can perform tasks from the convenience of their office without having to be present at the operation site. Recently, the potential of making such a capability was established with a very high resolution and large workspace using the concept of MEMICA (MEchanical MIRRORing using Controlled stiffness and Actuators) [<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 Electrically Controlled Force and Stiffness (ECFS) actuators. Using this system, the feeling of the stiffness and forces applied at remote or virtual environments may be reflected to the users via proportional changes in the viscosity of ERF. In Figure 9, a graphic presentation is showing a MEMICA simulator for the performance 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 such a capability may be applied to perform or practice inspection of aircraft and other structures while operating in the environment of a classroom.

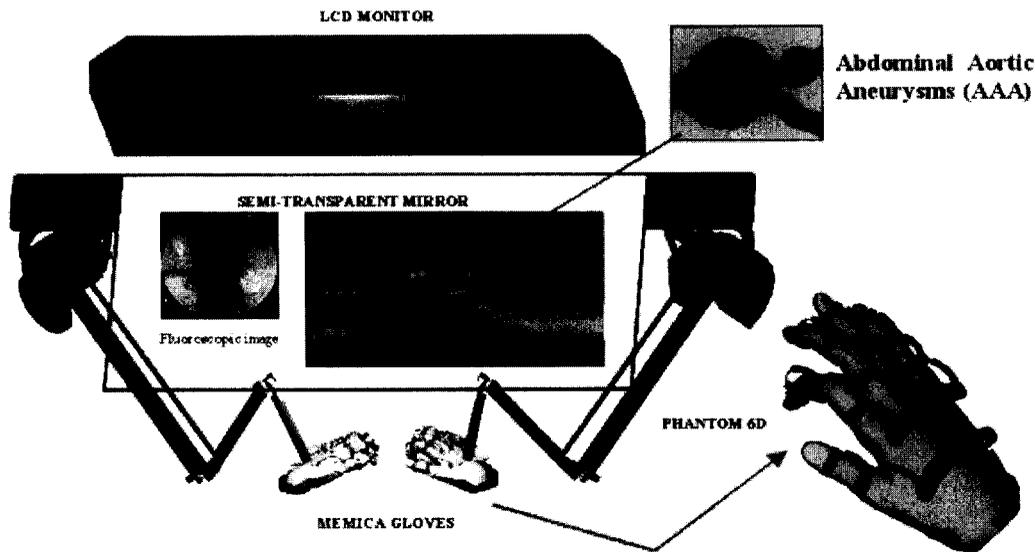


FIGURE 9: Performing virtual reality medical tasks via the Electro-Rheological Fluid based MEMICA haptic interface offers the potential of highly attractive interactive simulation system.

7. SUMMARY AND OUTLOOK

Electroactive polymers have emerged with great potential enabling the development of unique biomimetic devices. As artificial muscles, EAP actuators are offering capabilities that are currently considered science fiction. Developing such actuators is requiring development on all fronts of the field infrastructure. Enhancement of the performance of EAP will require advancement in related computational chemistry models, comprehensive material science, electro-mechanics analytical tools, and improved material processing techniques. In addition, a discipline of visco-elastic engineering and control strategies are needed to supplant the traditional engineering of rigid structures. Such development is enabling biologically inspired robotics and 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 is the development of haptic interfaces that employ an ERF-based MEMICA system to support a combination of tele-presence and virtual reality.

The recent trend of international cooperation, the greater visibility of the field and the surge in funding of related research projects are significantly helping to advance the field. To assist in the development of effective biomimetic 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 field. Progress towards winning this arm wrestling match will lead to exciting new generations of effective robots and is expected to benefit the development of prosthetics with functionalities that are close to realistic limbs. Robots that are biologically-inspired may perform combinations of locomotion techniques including walking, hopping, swimming, diving, crawling, flying, etc. with selectable behavior and operation characteristics. Making robots that are actuated by EAP as artificial muscles that are controlled by artificial intelligence would create a new science and technology realities. While such capabilities are expected to significantly change future robots, significant research and development effort is needed to develop robust and effective EAP-based actuators.

ACKNOWLEDGMENTS

The research related to electroactive polymers at the Jet Propulsion Laboratory (JPL), California Institute of Technology, was carried out under a DARPA contract with the National Aeronautics and Space Agency (NASA).

REFERENCES

- Bar-Cohen Y. (Ed.), *Proceedings of the SPIE's Electroactive Polymer Actuators and Devices Conf.*, 6th Smart Structures and Materials Symposium, Volume 3669, ISBN 0-8194-3143-5, (1999), pp. 1-414.
- 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 (2000a), pp.1-481.
- Bar-Cohen Y. (Ed.), *Proceedings of the SPIE's Electroactive Polymer Actuators and Devices Conf.*, 7th Smart Structures and Materials Symposium, Vol. 3987, ISBN 0-8194-3605-4 (2000b), pp 1-360.
- 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 2001a), pp. 1-671
<http://ndea.jpl.nasa.gov/nasa-nde/yosi/yosi-books.htm>
- Bar-Cohen Y. (Ed.), *Proceedings of the SPIE's Electroactive Polymer Actuators and Devices*, 8th Smart Structures and Materials Symposium, Vol. 4329, ISBN 0-8194-4015-9 (2001b), pp. 1-524.
- Bar-Cohen Y., and C. Breazeal (Book Eds), "Biologically-Inspired Intelligent Robots," SPIE Press (in preparation, expected to be published in 2002). Outline details on:
<http://ndea.jpl.nasa.gov/ndea-pub/Biomimetics/Biomimetic-robots-outline.pdf>
- Eguchi M., *Phil. Mag.*, Vol. 49, (1925)
- Katchalsky A., "Rapid Swelling and Deswelling of Reversible Gels of Polymeric Acids by Ionization", *Experientia*, Vol. V, (1949), pp 319-320.
- Kornbluh R., et al, "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", *Ann. Phys. Chem.* vol. 11, pp. 771-786, 1880
- Sacerdote M. P., *J. Physics*, 3 Series, t, VIII, 31 (1899).
- Zhang Q. M., T. Furukawa, Y. Bar-Cohen, and J. Scheinbeim (Editors), *Proceedings of the Fall MRS Symposium on "Electroactive Polymers (EAP)"*, ISBN 1-55899-508-0, Vol. 600, Warrendale, PA, (1999) pp. 1-336.