Proceedings of EAPAD, SPIE's 8th Annual International Symposium on Smart Structures and Materials, 5-8 March, 2001, Newport, CA. Paper No. 4329-02

Transition of EAP material from novelty to practical applications – are we there yet?

Yoseph Bar-Cohen
Jet Propulsion Laboratory (JPL)/Caltech[1]

Abstract

For many years, EAPs received relatively little attention due to their limited actuation capability and the small number of available materials. In the last ten years, new EAP materials have emerged that exhibit large displacement response to electrical stimulation and they are enabling great potentials for the field. EAP are very attractive for their operational similarity to biological muscles, particularly their resilience, damage tolerant, and ability to induce large actuation strains. The application of these materials as actuators to drive various manipulation, mobility and robotic devices involves multidiscipline including materials, chemistry, electro-mechanics, computers, electronics, etc. Even though the force actuation of existing EAP materials and their robustness require further improvement, there has already been a series of reported successes. The successful devices that were reported include miniature manipulation devices including catheter steering element, miniature manipulator, dust-wiper, miniature robotic arm, grippers and others. Some of the currently considered applications may be difficult to accomplish and it is important to scope the requirements to the level that current materials can address. Using EAP to replace existing actuators may be a difficult challenge and therefore it is highly desirable to identify a niche application where it would not need to compete with existing capabilities. This paper will review the current efforts and the expectations for the future.

Keywords: EAP, Artificial Muscles, EAP Actuators, Active Polymers, Medical EAP, Manipulators

1. Introduction

One of the most attractive characteristics of EAP materials is their potential to actuate biologically inspired systems (so-called biomimetic) that are lightweight, low power, inexpensive, damage tolerant, and agile. Various applications are currently being considered in an effort to take advantage of these unique characteristics [Bar-Cohen, 2001]. As the field is being advanced from a novelty and fascinating materials to actuators-of-choice it can be productive to evaluate the capabilities and challenges. Since the early 1990s, a series of new materials has emerged that exhibit significant electromechanical response. To assist potential users of EAPs in assessing the applicability of the various materials, the author divided them into two major groups: ionic and electronic. The general advantages and disadvantages of each these groups are listed in Table 1 and typical responses of example materials from each of these two groups are shown is Figure 1 and 2. In Figure 1 a starfish-shaped IPMC (Osaka National Research Institute, Japan) is shown to bend significantly. The direction of bending of ionomeric polymer-metal composites (IPMC) depends on the voltage polarity. In Figure 2 a dielectric film is shown (SRI International) with circular carbon grease electroded area that is activated by an electric field leading to expansion. Once the electric field is turned off the material contracts back to the original shape. This capability to generate a large stain cannot be matched by any alternative electroactive material including piezoceramics and shape memory alloys. However, these materials are still in their emerging stage and further development is needed to address the challenges to their practical application. Under the lead of the author, studies of potential planetary applications for these two types of material indicated a series of critical challenges. While the identified challenges are not common to all EAP materials or even to other ionic-types, this lesson learned shows some of the technical difficulties that need to be addressed.

2. Applications that are being explored

The challenge that the author posed to the science and engineering community to develop an EAP robotic arm that can win against a human in a wrestling match is continuing to be a distant possibility. This challenge is expected to be a long-term goal that may take at least 10 to 20 years to realize. However, there has been significant progress in the field of EAP towards technology the author initiated and is currently maintaining various forums including a series of related websites and issuing the semi-annual WW-EAP Newsletter [Bar-Cohen, started in 1999]. Some of the mechanisms and devices that are being

[1] JPL (MS 82-105), 4800 Oak Grove Drive, Pasadena, CA 91109-8099, yosi@jpl.nasa.gov, web: http://ndeaa.jpl.nasa.gov

making practical actuators that may lead to commercial devices within the period of the next five years. A growing number of organizations are now exploring potential applications for EAP and cooperation across many disciplines are needed to overcome some of the challenges. To assist in promoting collaboration among developers and potential users of the considered are related to aerospace, automotive, medical, robotics, exoskeletons, articulation mechanisms, entertainment, animation, toys, clothing, haptic and tactile interfaces, noise control, transducers, power generators and smart structures.

TABLE 1: A Summary of the advantages and disadvantages of the two basic EAP groups

EAP type	Advantages	Disadvantages
Electronic EAP	• Can operate in room conditions for a long time • Rapid response (mSec levels) • Can hold strain under DC activation • Induces relatively large actuation forces	• Requires high voltages (~150 MV/m) • Requires compromise between strain and stress • Glass transition temperature is inadequate for low temperature actuation tasks
Ionic EAP	• Large bending displacements • Provides mostly bending actuation (longitudinal mechanisms can be constructed) • Requires low voltage	• Except for CPs, ionic EAPs do not hold strain under DC voltage • Slow response (fraction of a second) • Bending EAPs induce a relatively low actuation force • Except for CPs, it is difficult to produce a consistent material (particularly IPMC) • In aqueous systems the material sustains hydrolysis at >1.23-V

2.1 Human-Machine Interfaces

Interfacing between human and machine to complement or substitute our senses can enable important capabilities for possible medical applications or general use. In the last five years a number of such interfaces, which employ EAP, were investigated or considered. Of notable significance is the ability to interface machines and the human brain. Such a capability addresses a critical element in the operation of prosthetics that may be developed using EAP actuators. A recent development by scientists at Duke University [Wessberg, et al, 2000] enabled this possibility where electrodes have been connected to the brain of a monkey and using brain waves of the monkey to operate a robotic arm, both locally and remotely via the internet. Using such a capability to control prosthetics would require feedback to allow the human operator to "feel" the environment around the artificial limbs. Such feedback can be provided with the aid of tactile sensors, haptic devices, and other interfaces. Some of the interfaces that are currently being explored include:

1. Haptic Interfacing – "Feeling" Virtual or Remote Stiffness and Forces (see Figure 3).
2. Simulated Texture:
3. Orientation Indicator – Smart Flight or Diving Suits

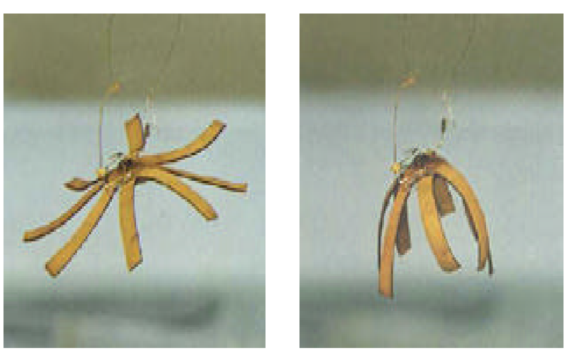
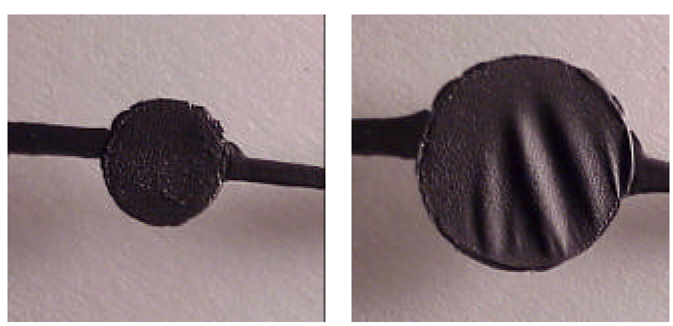
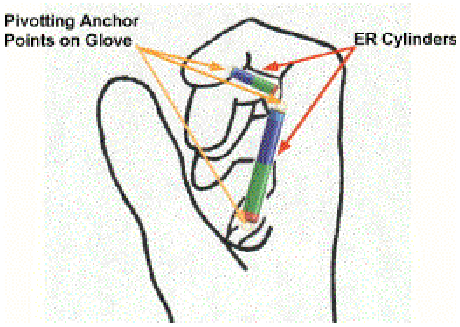


FIGURE 1: IPMC multi-finger starfish (Courtesy of K. Oguro, Osaka National Research Institute, Osaka, Japan).

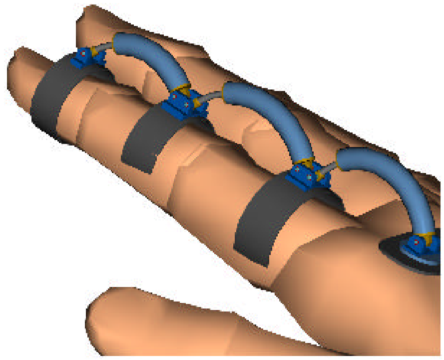


Voltage Off **Voltage On**

FIGURE 2: Dielectric actuator demonstrated to expand and relax. (Courtesy of R. Kornbluh and R. Pelrine, SRI International).



a. Glove with electrically controlled Stiffness (ESC) elements



b. Glove with exoskeleton ESC base actuator

c. Robonaut

FIGURE 3: A schematic view of the components of the haptic system, MEMICA allowing an operator to "feel" the stiffness at a virtual or remote site. Such a system can potentially mirror the mechanical response of such robots as the NASA's Robonaut.

2.2 Planetary Applications

The use of polymers in space has evolved to the level that flight hardware structures made of such materials are increasingly part of NASA exploration missions [Chmielewski and Jenkins, 2000]. Some of the applications include the 1997 Mars Pathfinder mission use of a balloon to cushion the landing and the IN-STEP Inflatable Antenna Experiment (shown in Figure 4), which flew on STS-76 on May 29, 1996 (concept developed by L'Garde, Inc.). Inflatable space structures can be produced to have very large surfaces that can be launched in a packed form and then inflated to shape and rigidize, creating large structures with a very low mass. An example of inflatable and rigidized synthetic aperture radar is shown in Figure 5. In order to obtain the maximum benefit from such structures there is a need to precisely control their shape either prior to rigidization or in real time when periodic deformation and shape control are needed. EAP materials offer the potential of providing the necessary actuation technology for such structures. Such gossamer structures are expected to enable missions that are significantly beyond the capabilities of current technologies. However, such capabilities can only be considered as a long-term goal given the current limitations of the EAP technology.

FIGURE 4: A Space Shuttle view of the L'Garde's Inflatable Antenna Experiment (IAE)

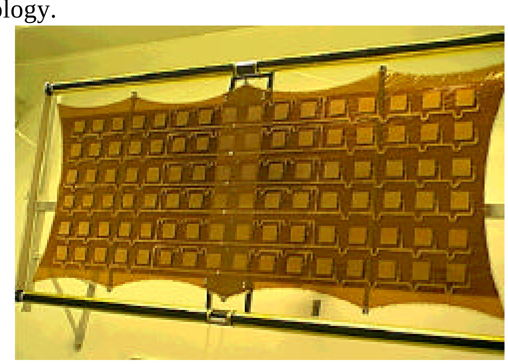


FIGURE 5: Inflatable and rigidized Synthetic Aperture Radar at the JPL

2.3 Controlled Weaving

Conventional fabrics that are used to make garments and clothing have passive properties. Using EAP fibers, which can consist of conductive polymers would enable a new era in clothing and gossamer structures allowing controlled configuration and shape. EAP fibers can be actuated and while maintaining flexibility, they offer the potential to adjust the thermal insulation of the clothing. Moreover, such fibers may support teleoperation and rehabilitation engineering. Sensors may be used to gauge the temperature, mechanical strain, or other properties to determine the desired action, shape, or state of the fabric weaving. At the University of Pisa and Santa Fe Science and Technology (New Mexico, USA), studies are underway to develop such fibers using a polyaniline working electrode core coated with solid electrolyte and a counter electrode [de Rossi, et al, 1999]. Voltage levels that are less than 2-Volt can be sufficient to drive these fibers, and they are expected to serve as controlled weaving. Some of the applications that are under consideration include antistatic clothing and membranes for chemical separation.

2.4 Robotics, Toys and Animatronics:

The potential capability of EAPs to emulate muscles may enable robotic capabilities that have been in the realm of science fiction when relying on existing actuation materials [Kennedy et al. 2001, & Hanson and Pioggia, 2001]. The large displacement that can be obtained using low mass, low power and, in some of the EAPs, also low voltage, makes them attractive for attempting to produce biologically inspired robots. EAP materials are being sought as a substitute for conventional actuators, possibly eliminating the need for motors, gears, bearings, screws, etc. Combining the bending and longitudinal strain capabilities of EAP actuators, a miniature robotic arm was designed and constructed at JPL. Experiments with this robotic arm raised concerns regarding the ability to control the kinematics of robotic components made of dielectric EAP and of IPMC since these actuators are flexible and do not provide accurate positioning. Upon activation, the arm exhibits low frequency vibration with a relatively low damping. The inherent vibration damping characteristics of polymers is not sufficient to suppress this low frequency vibration. Besides effective control algorithms, sensor feedback is expected to be critical to addressing this issue of precision positioning of EAP activated devices

2.5 Medical Applications

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 hearing aids, vocal cords, 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. To support such efforts, research is currently underway to establish a testbed (Figure 6) and models. Some of the medical applications that are currently being considered include:

1. EAP for Biological Muscle Augmentation or Replacement
2. Miniature in-Vivo EAP Robots for Diagnostics and Microsurgery:
3. Catheter Steering Mechanism (see Figure 7)
4. Tissues Engineering
5. Interfacing Neuron to Electronic Devices Using EAP
6. Active Bandage

FIGURE 6: A photographic view of a human hand and skeleton as well as an emulated structure for which EAP actuators are being sought (Courtesy of Graham Whiteley, Sheffield Hallam University, UK).

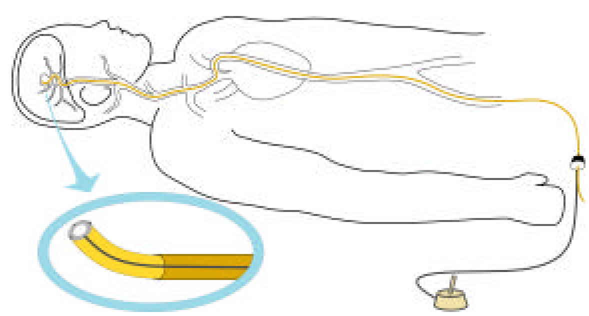


FIGURE 7: Active catheter guide using an IPMC type bending EAP (Courtesy of K. Oguro, Osaka National Research Institute, Osaka, Japan).

2.6 Noise Reduction

In recent years, concern about acoustic noise has grown significantly. Areas that need reduced noise include aircraft cabins, automobiles, and other noisy environments where comfort and hearing safety of the passengers, users, or operators may be affected. Suppressing unwanted noise can be done by passive and/or active noise control [Yang and Chen, 1999]. Active control is becoming a widespread method of reducing low frequency noise, which is difficult to address by passive control methods (including sound absorbers). However, these techniques are less effective in damping high frequency noise. A study is underway at the Industrial Technology Research Institute, Taiwan, to develop, such a noise suppression system that is activated by EAP. The use of the EAP film offers miniature, lightweight, low-cost actuators with large actuation displacement and high power output. The smart system that is under development uses hybrid passive-active control to address noise over a wide frequency range, and it consists of an EAP film, an air gap, and fibrous layer. The EAP film is used to minimize the reflected acoustic waves, and it operates as a loudspeaker, whereas the fibrous surface on the backside provides a feed forward least-mean-square (LMS) control.

3. Future Expectations

For many years, electroactive polymers (EAP) received relatively little attention due to their limited actuation capability and the small number of available materials. In recent years, there has been an emergence of several new EAP materials that exhibit large displacement in response to electrical stimulation. This capability of the new materials is making EAP attractive as actuators for their operational similarity to biological muscles, particularly their resilience, damage tolerance, and ability to induce large actuation strains (stretching, contracting or bending). The application of these materials as actuators to drive various manipulation, mobility, and robotic devices involves multi-disciplines, including materials, chemistry, electromechanics, computers, and electronics. Even though the force of actuation of existing EAP materials and their robustness require further improvement, there has already been a series of reported successes in the development of EAP actuated mechanisms. Successful devices that have been reported include a catheter steering element, miniature manipulator and robotics, miniature robotic arm, gripper, loudspeaker, active diaphragm, and dust-wiper. Using EAP to replace existing actuators may be a difficult challenge and therefore it is highly desirable to identify a niche application where EAP materials would not need to compete with existing technologies. Upon identifying such applications and emergence of EAP driven product, one can expect a rapid evolutionary improvements that will propel the capabilities and nurture a wide range of technology transfers. The enhancement of the actuation capability of EAP materials is studied on the fundamental level using computational chemistry and the predictions would need to be implemented by developing new synthesis techniques. The large strain response of EAP to electrical stimulation is nonlinear and requires adequate analytical tools for the design and control of related devices. Efforts are currently being made to model this nonlinear electromechanical behavior and to develop experimental techniques of material properties measurements and characterization. These efforts are leading and continue to contribute to better understanding of the origin of the electro-activity in various EAP materials, allowing improvement of their performance, and offering effective design tools for simulation of the performance of related devices. Methods of producing EAP fibers and films are being studied to effectively operate them as actuators and sensors and to improve their robustness. The author is hoping to see the day when an arm-wrestling match between a robot driven by EAP and human is won by the robot because reaching this milestone requires a level of EAP performance that would allow making devices that emulate many of the physical functions that human can perform.

Acknowledgement

The research at Jet Propulsion Laboratory (JPL), California Institute of Technology, was carried out under a contract with National Aeronautics Space Agency (NASA) and Defense Advanced Research Projects Agency (DARPA). Special thanks to the team members of his Telerobotic task LoMMAs that was funded by the NASA Code S program. The author would like to acknowledge the contribution of Dr. Sean Leary, Mark Schulman, Dr. Tianji Xu, and Andre H Yavrouian, JPL, Dr. Joycelyn Harrison, Dr. Joseph Smith, and Ji Su, NASA LaRC, Prof. Richard Claus, VT, Prof. Constantinos Mavroidis, and Charles Pfeiffer, Rutgers University.

References

Bar-Cohen Y. (Ed.) "Worldwide Electroactive Polymers Newsletter," JPL's NDEAA Technologies, http://ndeaa.jpl.nasa.gov/nasa-nde/lommas/eap/WW-EAP-Newsletter.html, started in June 1999.

Bar-Cohen Y. (Editor), "Electroactive Polymer (EAP) Actuators as Artificial Muscles - Reality, Potential and Challenges," SPIE Press, To be published February 2001.

Chmielewski A. B. and C. H. Jenkins "Flexible Load-Bearing Structures (Including Inflatables)," Chapter 5, *Structures Technology for Future Aerospace Systems*, Ahmed Noor (Ed.) AIAA Progress in Astronautics and Aeronautics Series, (expected to be published in 2000) de Rossi D., A. Della Santa and A. Mazzoldi, "Dressware: Wearable Hardware," Elsevier Science, Materials Science and Engineering C, Vol. 7 (1999) pp. 31-35.

Hanson D., and G.. Pioggia, Applications of EAP to Entertainment Industry -- Chapter 18.0 "Electroactive Polymer (EAP) Actuators as Artificial Muscles - Reality, Potential and Challenges," Bar-Cohen Y. (Ed.), SPIE Press, To be published February 2001.

Kennedy B., C. Melhuish, and A. Adamatzky, "Biologically-inspired Robots," Chapter 17.0, "Electroactive Polymer (EAP) Actuators as Artificial Muscles - Reality, Potential and Challenges," Bar-Cohen Y. (Ed.), SPIE Press, To be published February 2001.

Wessberg J., C. R. Stambaugh, J. D. Kralik, P. D. Beck, M. Lauback, J.C. Chapin, J. Kim, S. J. Biggs, M. A. Srinivasan and M. A. Nicolelis, "Real-time Prediction of Hard Trajectory by Ensembles of Cortical Neurons in Primates," Nature, Vol. 408, (16 November 2000), pp. 361-365

Yang T. L., and W. –H. Chen, "EAP Smart Noise Reduce System & Heat Dissipation Device," WW-EAP Newsletter, Vol. 1, No. 2 http://ndeaa.jpl.nasa.gov/nasa-nde/lommas/eap/WW-EAP-Newsletter.html, (1999), p. 9-10.