ELECTROACTIVE POLYMERS AS ARTIFICIAL MUSCLES CHANGING ROBOTICS PARADIGMS

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For many years, electroactive polymers (EAP) received relatively little attention due to the small number of available materials and their limited actuation capability. The recent emergence of EAP materials with large displacement response enabled great potentials for these materials. The main attractive characteristic of EAP is their operational similarity to biological muscles, particularly their resilience and ability to induce large actuation strains. Unique robotic components and miniature devices are being explored, where EAP serve as actuators to enable new capabilities. These new capabilities are changing the paradigm of robotics in terms of components and performance. In recognition of the need for international cooperation among the developers, users and potential sponsors, an SPIE Conference was organized for the first time on March 1-2, 1999, in Newport Beach, California. The conference was the largest ever on EAP, and it marked an important milestone, turning the spotlight onto these emerging materials and their potential. Following this success, an MRS conference was initiated to address the fundamental issues related to the material science of EAP. The WW-EAP newsletter was initiated to bring the worldwide EAP community even closer. A homepage was also created to link worldwide EAP research and development facilities websites. In this paper, the current capabilities and potentials as well as the challenges of state-of-the art EAP will be reviewed.

INTRODUCTION

The recent introduction of polymers that induce large strain under electrical activation led to their consideration as potential actuators. The level of induced strain can be as high as two orders of magnitude greater than the striction-limited, rigid and fragile electroactive ceramics (EAC). Also, they are superior to shape memory alloys (SMA) in their spectral response, lower density, and resilience. Generally, EAP are electrically hard and mechanically soft. Particularly, ferroelectric polymers have a coercive field in the range of 100 V/μm, which is of the order of 100 times the coercive fields of ceramic ferroelectrics making polymers quite stable electrically. On the other hand, EAP materials reach their elastic limit at lower stress levels compared to EAC, and their actuation stress falls far shorter than EAC and SMA actuators. In Table 1 a comparison is given between EAP, EAC and SMA and it is easy to see the properties in which EAP offer superior capability.

The most attractive feature of EAPs is their ability to emulate biological muscles offering resilience, toughness, large actuation strain and inherent vibration damping. This similarity gained them the name "Artificial Muscles" with the potential of developing biologically inspired robots. Biomimetic robots actuated by EAP can be made highly maneuverable, noiseless and agile, with various shapes and they can enable to make science fiction ideas a faster reality than would be feasible with any other conventional actuation mechanisms. Unfortunately, at present the force actuation and mechanical energy density of EAPs are relatively low, limiting the potential applications that can be considered. In recognition of the need for international cooperation among the developers, users and potential sponsors, the author organized though SPIE International the first EAP Conference on March 1-2, 1999. This Conference was held in Newport Beach, California, USA and was the largest ever on this subject, making an important milestone, and turning the spotlight onto these emerging materials and their potential. Following this success, MRS conference was initiated to address the fundamental issues related to the material science of EAP. Further, the author established a homepage linking websites of worldwide EAP research and development facilities (http://ndeaa.jpl.nasa.gov/nasa-nde/lommas/eap/EAP-web.htm). Also, he initiated the publication of the WW-EAP Newsletter, which is published electronic (http://eis.jpl.nasa.gov/ndeaa/nasa-nde/newsltr/WW-EAP_Newsletter.PDF). He also helped establishing the WW-EAP Newsgroup.

TABLE 1: Comparison of the properties of some actuation materials

Property	Electro-static silicone elastomer [Perline]	Polymer Electrostrictor [Zhang]	SMA	Single Crystal Electrostrictor [Park]	Single Crystal Magnetostrictor [Hathaway]
Actuation strain	32 %	4 %	8 %	1.7 %	2 %
Blocking Force/Area *	0.2 MPa	0.8 MPa	700 MPa	65 MPa	100 MPa
Reaction speed	μsec	μsec	sec to min	μsec	μsec
Density	1.5 g/cc	3 g/cc	6 g/cc	7.5 g/cc	9.2 g/cc
Drive field	144 V/μm	150 V/μm	--	12 V/μm	2500 Oe
Fracture toughness	large	large	large	low	large

*Note: Values were calculated assuming the elastic properties were independent of applied field and are therefore approximated.

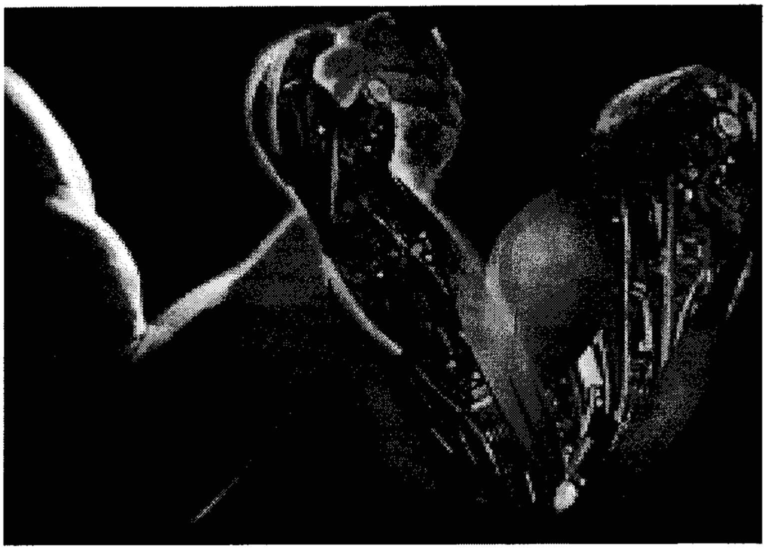

FIGURE 1: Grand challenge for the EAP community.

The increased resources, the growth in number of investigators conducting EAP related research, and the improved collaboration among developers, users and sponsors are all expected to lead to rapid progress in the coming years. Recently, the principal author challenged the worldwide community of EAP experts to develop a robotic arm that is actuated by artificial muscles to win a wrestling match with a human opponent (Figure 1). Progress towards this goal will lead to great benefits, particularly in the medical area, including effective prosthetics. Decades from now, EAP may be used to replace damaged human muscles, 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.

NEED FOR AN EFFECTIVE EAP INFRASTRUCTURE

Construction of mobility or articulation system that is actuated by EAP requires components as shown in Figure 2 as a block diagram. While each of the listed components is at various advanced research phases, EAP actuators are the least developed technology and extensive effort is required to bring it to a mature stage. Unfortunately, the EAP materials that emerged so far are still exhibiting low force, are not effective and there are no commercially available robust materials for consideration in practical applications. In recent years, a series of EAP materials that induce large strain were documented, including carbon nanotubes, ferroelectric, electrostrictives, ion exchange membranes, conductives, electrostatics and piezoelectrics [Bar-Cohen, 1999a]. In order to be able to transition these materials from development phase to effective actuators there is a need to establish an adequate “EAP infra-structure”. The author’s view of this infrastructure and the areas needing simultaneous development are shown schematically in Figure 3. This involves the need for adequate understanding of EAP materials' behavior and the necessity to assure their durability in service. Enhancement of the actuation force requires knowledge of the basic principles using computational chemistry models, comprehensive material science, electro-mechanics analytical tools and improved materials processes. Efforts are needed 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 will need to be refined to maximize their actuation capability and robustness. Methods of reliably characterizing the response of these materials are required to allow documenting the material properties to support design engineering towards making EAP the actuators of choice. Various configurations of EAP actuators, sensors and potential MEMS will need to be studied and modeled to produce an arsenal of effective actuators. The development of the infrastructure is multidisciplinary and requires international collaboration.

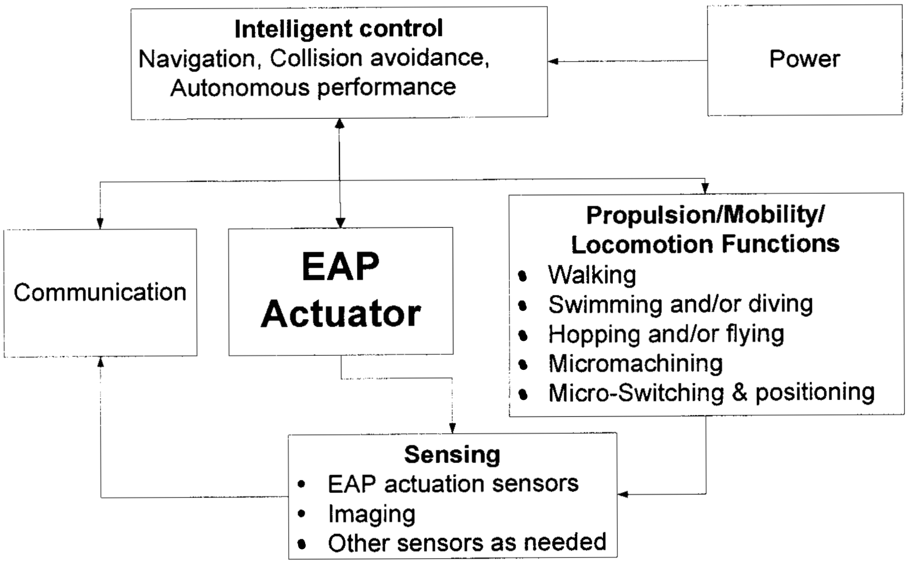

FIGURE 2: A schematic diagram of the basic components of an EAP-driven system.

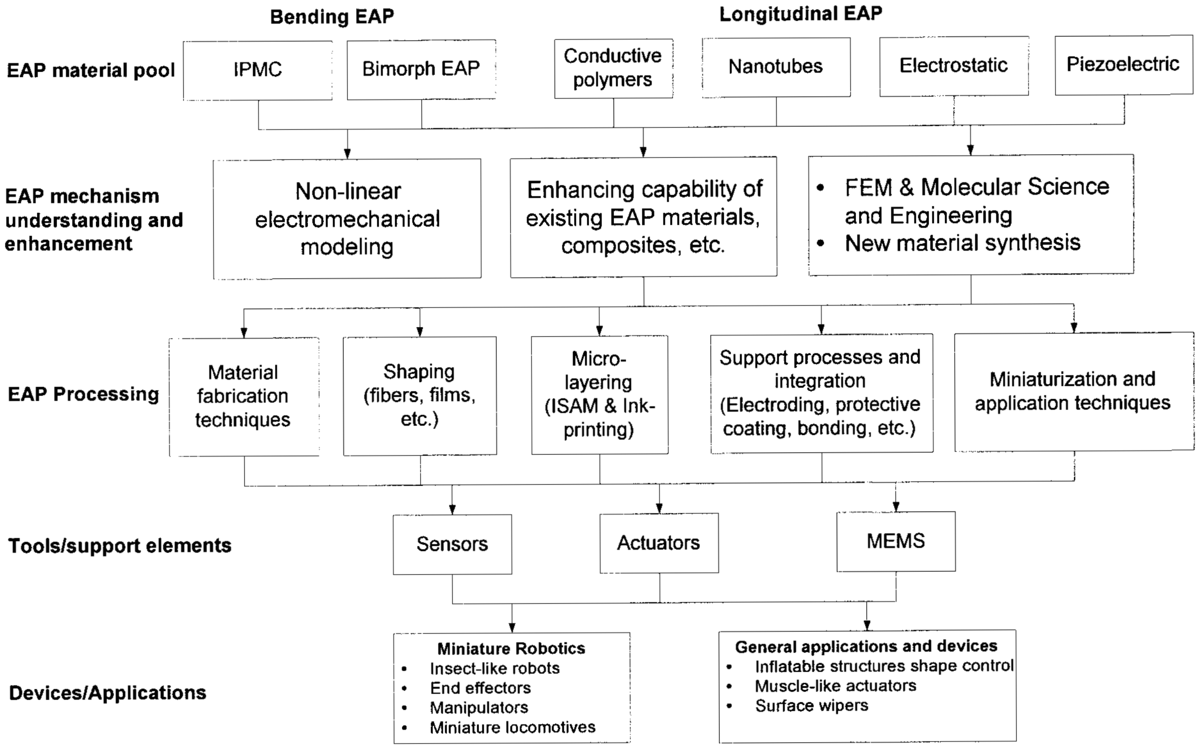

FIGURE 3: EAP infrastructure and areas needing attention.

BIOLOGICAL MUSCLES

Developing intelligent robots requires the combination of strong muscles (actuators) and acute sensors, as well as the understanding of the biological model. Using effective EAP materials as artificial muscles, one can develop biologically inspired robots and locomotives that can possibly walk, fly, hop, dig, swim and/or dive. Natural muscles are driven by a complex mechanism and are capable of lifting large loads at short (millisecond) response times. The performance characteristics of muscles are difficult to measure and most measurements were made on large shell-closing muscles of scallops. Peak stress of 150-300-KPa is developed at a strain of about 25%. Maximum power output is 150 to 225-W/kg; average power is about 50-W/kg with an energy density of 20-70-J/kg, which decreases with the increase in speed. Since muscle is fundamental to animal life and changes little between species, we can regard it as a highly optimized system. It is a system that depends on chemically driven reversible hydrogen bonding between two polymers, actin and myosin. Muscle cells are roughly cylindrical, with diameters between 10 and 100-μm and up to few centimeters long. Although muscles produce linear forces, motions at joints are all rotary. Therefore, the strength of an animal is not just muscle force, but muscle force as modified by the mechanical advantage of the joint [Alexander, 1988], which usually varies with joint rotation. The mechanical energy is provided by a chemical free energy of a reaction involving adenosine triphosphate (ATP) hydrolysis. The release of Ca+2 ions seems turning on and off the conformational changes associated with muscle striction.

The mobility of insects is under extensive study and there is a relatively large body of knowledge in place, as for example at the University of California, Berkeley [Full and Tu, 1990]. A windmill was used with a photoelastic coating to study the details of insects walking mechanisms, where insects with various numbers of legs were investigated. Also, the size of electronic devices has become so small that insects can be instrumented to perform tasks once viewed as science fiction. At the University of Tokyo, Japan, a spider and other insects were instrumented as locomotives to carry backpacks of wireless electronics [http://www.leopard.t.u-tokyo.ac.jp/]. Development of EAP actuators is expected to enable insect-like robots that can be launched into hidden areas of structures to perform inspection and various maintenance tasks. In future years, EAP may emulate the capabilities of biological creatures with integrated multidisciplinary capabilities to launch space missions with innovative plots. Some biological functions that may be adapted include soft-landing like cats, traversing distances by hopping like a grasshopper and digging and operating cooperatively as ants.

CURRENTLY AVAILABLE EAP MATERIALS

The beginning of the field of EAP can be traced back to Roentgen reporting in 1880 the electro-activation of rubber-band that is charged and discharged while one end fixed and with a mass attached to the free end. This milestone was followed in 1925 by the discovery of an electret when carnauba wax, rosin and beeswax are solidified by cooling while subjected to DC bias field [Eguchi, 1925]. Generally, electrical excitation in only one of the mechanisms that can be used to induce elastic deformation in polymers [Perline, et al, 1998, and Zhang, et al, 1998]. Other activation mechanisms include chemical [Kuhn, et al, 1950; Steinberg, et al, 1966; and Otero, et al, 1995], thermal

[Tobushi, et al, 1992; and Li, et al, 1999], magnetic [Zrinyi, et al, 1997], and optical [van der Veen & Prins, 1971]. Polymers that are chemically stimulated were discovered before half a century when collagen filaments were demonstrated to reversibly contract or expand when dipped in acid or alkali aqueous solutions, respectively. Even though very little has since been done to exploit such 'chemo-mechanical' actuators, this early work pioneered the development of synthetic polymers that mimic biological muscles [Steinberg, et al, 1966]. The convenience and the practicality of electrical stimulation and the technical progress led to a continuously growing emphasis on 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 [Bar-Cohen, et al, 1996; and Oguro, et al 1999]. While the list of such EAP has grown considerably, PVF2-TrFE is the only material that can be obtained commercially. Generally, EAP can be divided into two categories: Wet (ionic) and dry. The dry polymers (electrostrictive, electrostatic, piezoelectric and ferroelectric) require high activation field (>100-V/μm) that is close to the breakdown level. However, they can be made to hold DC voltage induced displacement allowing considerations for robotic applications. Also, these materials have a greater mechanical energy density. In contrast, wet EAP materials (ion-exchange, conductive polymers, gels, etc.) require drive voltages as low as 1-2 Volts. However, there is a need to maintain their wetness and it is difficult to sustain DC-induced displacements. The induced displacement of both the dry and wet EAP can be either bending or stretching/contraction. Overall, any of the EAP material can be made to bend with a significant curving response, which appears appealing. However, such actuators have relatively limited potential applications due to the low force or torque that can be induced. The materials can be divided into two types and their advantages and disadvantages for actuation applications are listed in Table 3.

TABLE 3: The types of EAP materials that are currently known and their advantages and disadvantages for actuation applications.

EAP type	**Advantages**	**Disadvantages**
Dry	• Can operate in room conditions for a long time • Can respond at very high frequencies • Provide large actuation forces	• Requires high voltages • Compromise between strain and stress is needed
Wet (Ionic)	• Provides mostly bending actuation (longitudinal mechanisms can be articulated) • Large bending displacements • Sustain hydrolysis at >1.23-V • Requires low voltage	• Does not hold strain under DC voltage • Operates at low frequencies (several Hertz) • Bending EAP presents a vary low actuation force

DEVELOPMENT OF EAP FOR SPACE APPLICATIONS

Since 1995, under the author's lead, planetary applications using EAP have been explored while improving the understanding, practicality and robustness of these materials. EAP materials are being sought as a substitute to conventional actuators, and possibly eliminating the need for motors, gears, bearings, screws, etc. [Bar-Cohen, et al, 1999b]. Generally, space applications are the most demanding in terms of operating conditions, robustness and durability offering an enormous challenge and great potential for these materials. Under this NASA funded effort, ESSP and IPMC were used to produce longitudinal and bending actuators, where a dust-wiper, gripper and robotic arm were demonstrated. The development of a dust-wiper (Figure 4) has received the most attention and it was considered for the Nanorover's optical/IR window, which is part of the MUSES-CN mission. The MUSES-CN is a joint NASA and the NASDA (National Space Development Agency of Japan) mission scheduled for launch in January 2002, from Kagoshima, Japan, to explore the surface of a small near-Earth asteroid. The use of IPMC was investigated jointly with NASA LaRC, USA, and Osaka National Research Institute and Kobe University from Japan. The team used perfluorocarboxylate-gold composite with two types of cations, tetra-n-butylammonium and lithium. The IPMC was used as the actuator that wipes the window with a unique 104-mg blade having fiberglass brush, which was developed by ESLI (San Diego, CA). This blade is subjected to high voltage (~1.5-KV) to repel dust and thus augmenting the brushing mechanism provided by the blade. Unfortunately, the critical issues that affect the application of IPMC hampered the consideration of launching the dust-wiper in this mission.

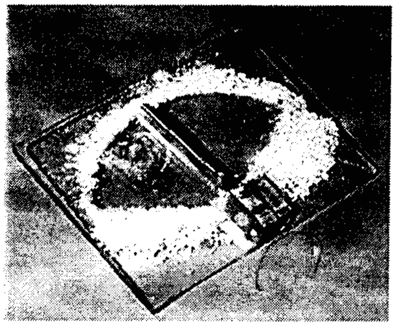

FIGURE 4: Schematic view of the EAP dust-wiper.

Another application of EAP actuators, having even lower technology readiness, which was considered, is the development of a miniature robotic arm (Figure 5 and 6). An ESSP actuator was used to lift and drop the arm, whereas a 4-finger IPMC gripper was used to grab rocks and other objects. When grabbing rocks, the four fingers operate much like a human hand (see Figure 8).

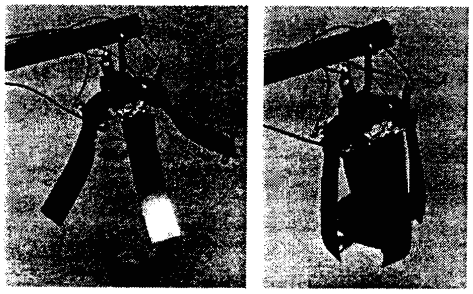

FIGURE 5: 4-finger EAP gripper lifting a rock much like a human hand.

FIGURE 6: A miniature robotic arm using EAP actuators to provide the lifting/dropping of the arm and manipulate the gripper fingers.

CONCLUDING REMARKS

In recent years, electroactive polymers have emerged with great potential to enable unique mechanisms, which can emulate biological systems. Efforts to apply such materials to space applications revealed critical challenges that cannot be address with current technology. Much more research and development work still needs to be done before EAP will become the actuators of choice. The development of an effective infrastructure for this field is critical to the commercial availability of robust EAP actuators for practical applications. The challenges are enormous, but the recent international trend towards more cooperation, the greater visibility of the field and the surge in funding related research are offering great hope for the future of these exciting materials. The potential to operate biologically inspired mechanisms driven by EAP as artificial muscles is offering capabilities that are currently considered science fiction. To highlight this potential, the EAP science and engineering community was challenged to develop a robotic hand actuated by EAP that would win an arm-wrestling match against human opponent. Progress towards this goal will lead to great benefits to mankind particularly in the medical area including effective prosthetics.

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