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The Electroactive Polymers Infrastructure

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

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 EAP that are robust for practical applications there is a need to establish an adequate EAP infrastructure. This requires developing adequate understanding of EAP materials' behavior, as well as effective processing and characterization techniques. Enhancement of the actuation force necessitates understanding the basic principles using computational chemistry models, comprehensive material science, electro-mechanics analytical tools and improved material processing techniques. Efforts are needed 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 need to be refined to maximize the EAP materials actuation capability and robustness. Methods of reliably characterizing the response of these materials are required to establish database with documented material properties in order to support design engineers considering use of these materials and towards making EAP as actuators of choice. Various configurations of EAP actuators and sensors 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 reviews the status of the EAP infrastructure and the challenges to practical application of EAP materials as actuators.

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 capability of these new EAP materials is attracting the attention of engineers and scientists from many different disciplines. The behavior similarity of these materials to biological muscles acquired them the moniker "artificial muscles" [1]. 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 actuation force, mechanical energy density and robustness of 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 [2-4]. This conference was followed with the organization of the MRS conference on EAP [5] Further, a website was formed with links to homepages of EAP research and development facilities worldwide (http://ndeaa.jpl.nasa.gov/nasa-nde/lommas/eap/EAP-web.htm), and a semi-annual Newsletter is being issued electronically (http://ndeaa.jpl.nasa.gov/nasa-nde/lommas/eap/WW-EAP-Newsletter.html).

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

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, 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 area, including effective prosthetics. Decades from now, EAP may be used to replace damaged human muscles, potentially leading to a "bionic human." A remarkable contribution of the EAP field would be to one day see a handicapped person jogging to the grocery store using this technology.

2. HISTORICAL REVIEW

The beginning of the field of EAP can be traced back to an 1880 experiment that was conducted by Roentgen [6] using a rubber-band that was charged and discharged with fixed end and a mass attached to the free end. Sacerdote [7] 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 [8]. Electrical excitation is only one of the polymers stimulators that can induce elastic deformation. Such stimulators can cause volume or shape change due to perturbation of the balance between repulsive intermolecular forces that 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 thus be controlled by subtle changes in parameters such as solvent or gel composition, temperature, pH, light, etc. The type of polymers that can be activated by non-electrical means include [1]:

- Chemically Activated
- Shape Memory Polymers
- Inflatable Structures, including McKibben Muscle
- Light Activated Polymers
- Magnetically Activated Polymers
- Thermally Activated Gels

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 [9]. 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 [10-11], 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 strains that exceed 300% have emerged [12].

4. ELECTROACTIVE POLYMERS (EAP)

Polymers that exhibit shape change in response to electrical stimulation can be divided into two distinct groups: electric (driven by electric field or Coulomb forces) and ionic (involving mobility or diffusion of ions). The electronic polymers (electrostrictive, electrostatic, piezoelectric, and ferroelectric) can be made to hold the induced displacement under activation of a DC voltage, allowing them to be considered for robotic applications. Also, these materials have a greater mechanical energy density and they can be operated in air with no major constraints. However, they require a high activation fields (>100-V/μm) close to the breakdown level. In contrast, ionic EAP materials (gels, polymer-metal composites, conductive polymers, and carbon nanotubes.) require drive voltages as low as 1-2 Volts. However, there is a need to maintain their wetness, and except for conductive polymers it is difficult to sustain DC-induced displacements. The induced displacement of both the electronic and ionic EAP can be geometrically designed to bend, stretch or contract. Any of the existing EAP materials can be made to bend with a significant curving response, offering actuators with an easy to see reaction and an appealing response. However, bending actuators have relatively limited applications due to the low force or torque that can be induced. A summary of the advantages and disadvantages of the two EAP groups is given in Table 1. The materials in each of these two EAP group [1] include:

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	• Requires low voltage • Provides mostly bending actuation (longitudinal mechanisms can be constructed) • Exhibit Large bending displacements	• Except for CP, 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 CP and CNT, it is difficult to produce a consistent material (particularly IPMC) • In aqueous systems the material sustains hydrolysis at >1.23-V

ELECTRIC EAP

- Dielectric EAP
- Electrostrictive Graft Elastomers
- Electrostrictive Paper
- Electro-Viscoelastic Elastomers
- Ferroelectric Polymers
- Liquid Crystal Elastomer (LCE) Materials

IONIC EAP

- Carbon Nanotubes (CNT)
- Conductive Polymers (CP)
- ElectroRheological Fluids (ERF)
- Ionic Polymer Gels (IPG)
- Ionomeric Polymer-Metal Composites (IPMC)

The induced displacement of both EAP groups can be designed to bend, stretch or contract. Making them to bend with a significant curving response offers an appealing easy to see reaction. However, due to the low force or torque that can be induced, bending actuators have relatively limited applications.

5. 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 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 still exhibiting low conversion efficiency, are not robust, and there are no standard commercial materials available for consideration in practical applications. The documented EAP materials that induce large strains are driven by many different phenomena [1-5]. Each of these materials requires adequate attention to the unique material characteristics and constraints. In order to be able to take these materials from the development phase to use 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 (Figure 1).

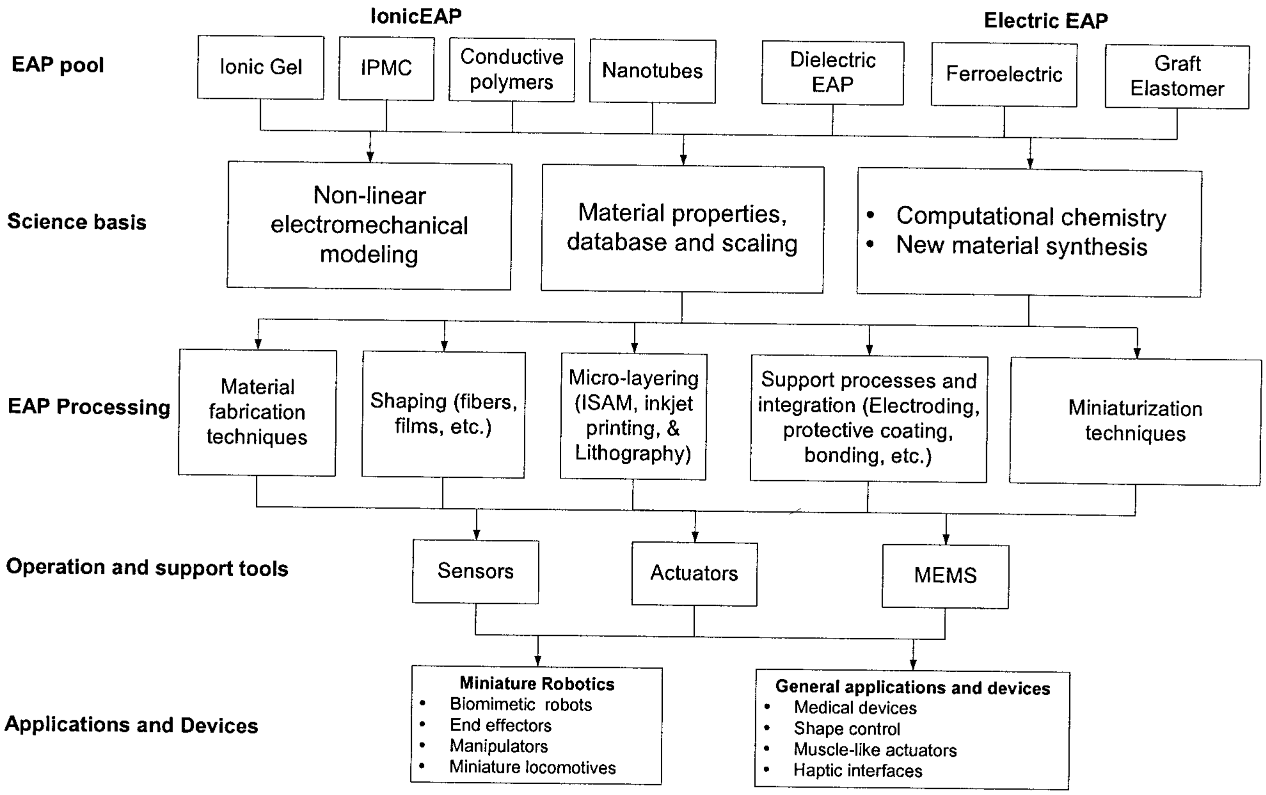

FIGURE 1: EAP infrastructure block diagram

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. 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 the EAP materials actuation capability and robustness. Methods of reliably characterizing the response of these materials are required to establish database with documented material properties in order to support design engineers considering use of these materials and towards making EAP as actuators of choice. Various configurations of EAP actuators and sensors will need to be studied and modeled to produce an arsenal of effective smart EAP driven system. 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 [1]. Each element of the block diagram shown in Figure 1 has been addressed as can be seen from the conference proceedings of the SPIE and MRS conferences on this subject [2-5]. 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 these materials will be exploited and commercial product will emerge in spite of the current limitations of EAP materials.

6. CONCLUSIONS

Electroactive polymers have emerged with great potential and enabled the development of unique devices that are biologically inspired. The development of an effective infrastructure for this field is critical to the commercial availability of robust EAP actuators and the emergence of practical applications. The challenges are enormous, but the recent trend of international cooperation, the greater visibility of the field and the surge in funding of related research are offering great hope for the future of these exciting new materials. The potential to enable biologically inspired mechanisms that are driven by EAP as artificial muscles will allow making engineering reality using ideas that currently considered science fiction. The author's arm-wrestling challenge for a match between EAP-actuated robots and a human opponent highlights the potential of EAP. Progress towards this goal will lead to great benefits to mankind particularly in the area of medical prosthetics.

7. ACKNOWLEDGEMENT

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