Electroactive Polymer Actuators and Devices

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Electroactive Polymer Actuators and Devices

Yoseph Bar-Cohen
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4 PAN, Gels, and Polypyrrole-based EAP
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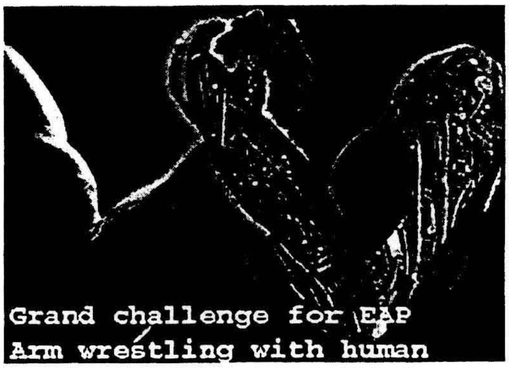
Introduction

For many years, electroactive ceramic and shape memory alloys have been the primary source of actuation materials for smart structures and movement mechanisms. Numerous applications have been reported, including robotics, active damping, vibration isolation, manipulation, articulation, and many other functions. Electroactive polymers (EAP) received relatively little attention due to the small number of available materials, as well as their limited actuation capability.

In recent years, new and effective EAP materials have emerged that are changing the view of these materials' capability and potential. Their main attractive characteristic is their similarity to biological muscles and their ability to induce large displacements. The ion-exchange membrane-bending EAP has even been shown to operate at very low temperatures and in a vacuum, thus, paving the path for its use for space mechanisms. Unique robotic components and miniature devices were reported, where EAP provided the actuation mechanism. Insectlike mechanisms driven by EAP are becoming a possible reality, and new enabling technologies are now feasible. In this conference, efforts were made to turn the spotlight onto these materials and their applications, as well as to increase the recognition of EAP as a viable option for smart structures.

A challenge was posed to the participants of the conference and the EAP science and engineering community: to develop a robotic hand that is actuated by EAP and could win against a human in an arm wrestling match. Progress toward 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 the "bionic human" of the future. My hope is to see someday a handicapped person jogging to the grocery store using this technology.



The conference included papers on the following topics:

- Electroactive polymer (EAP) materials and their characteristics,
- Models, analysis, and simulation of EAP,
- Biological muscles as a potential model for EAP actuators,
- EAP as artificial muscles, actuators, and sensors,
- Support technologies for electroactive polymers, and
- MEMS and robotic applications of electroactive polymer actuators, including miniature robo-creatures.

About 50 papers were received in support of this emerging technology area. The conference was well attended by leading world experts in the field, as well as by members of academia, industry, and government agencies from the U.S. and overseas who are interested in the technology. The conference was followed by a session entitled "EAP in Action," which was intended to give the participants hands-on experience with the various leading EAP materials, and included seeing videos that demonstrate EAP materials in action. To build on the unique opportunity that was formed with the gathering of the world-leading EAP experts, four action items were taken:

- An ElectroActivePolymers newsgroup was formed to serve as an electronic e-mail distribution system for communication among the EAP experts, producers, and users.
- The journal *Materials Science and Engineering C*, Editors: P. Calvert, D. De Rossi, T. Tateishi (Elsevier) was suggested to serve as a leading journal for the publication of EAP papers.
- A web page was formed listing hotlinks to leading EAP organizations worldwide. The address of this JPL web site is: **http://ndeaa.jpl.nasa.gov/nasa-nde/lommas/eap/EAP-web.htm**.
- An electronic *EAP Newsletter* will be published on a quarterly basis starting June 1, 1999, and will be distributed via the newsgroup e-mail address. A copy will be archived on **http://ndeaa.jpl.nasa.gov**.

In closing, I would like to extend a special thanks to all the conference attendees, session chairs, and members of the program committee. In addition, a special thanks is extended to the SPIE staff who worked very closely with the program committee and myself to make this conference a success.

Yoseph Bar-Cohen

Contents

Keynote Address

Electroactive Polymer Actuators and Devices

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ABSTRACT

The application of electroactive polymers (EAP) for mechanical actuation is discussed. A comparison is made between established actuation technologies and polymer actuators. In addition, mammalian muscle properties are compared to some of the observed polymer actuation properties. This paper attempts to analyze actuator performance metrics, as set for current technologies, to determine the feasibility of electroactive polymer actuators in various applications. In this analysis, different mechanical design approaches are reviewed for possible use in EAP actuator applications. Examples of EAP microactuators are presented.

Keywords: Electroactive polymers, actuator, actuation, robotics

1. INTRODUCTION

Over the last year, the Defense Advanced Research Projects Agency (DARPA) has begun a major new initiative in the demonstration of electroactive polymers (EAPs) in devices of interest to the Department of Defense (DoD). This initiative has offered a unique perspective on the capabilities and limitations of this interesting class of material. The purpose of this paper is to discuss potential applications for these materials, as well as their current limitations, and to offer a significant challenge to those engaged in the research and development of these materials. No attempt will be made to provide in this paper a detailed understanding of the chemistry and mechanisms of electroactive polymers (EAPs). The papers that follow, as well as many others that have been published,[1-7] address these issues adequately. However, a brief discussion of the characteristics of EAPs is necessary in order to understand the desire of DoD to pursue research in this area.

EAPs are defined here as polymers that can be formulated to have a wide range of electronic and/or electro-optical properties that can be tailored through the chemical composition and structure of the polymers themselves. Interestingly, these properties can often be made to change in response to external stimuli such as applied electric or magnetic field, light, pH, and stress. These changes often manifest themselves in modifications to the physical properties of the polymers, the most important of which is a change in dimension as a result of electrochemical alterations within the polymer – the basis for using these materials as actuators. Because these aforementioned responses are inherent in the internal structure of the polymer, EAPs are in some sense "intrinsically" smart materials.

Table I: Defense Applications for Electroactive Polymers

Actuation and Sensing
- Artificial Muscles
- Smart Skins
- Acoustic (Sonar)
- Biomimetic Devices

Electro-Optical Response
- Analog Processing
- Large Area, Flexible Displays
- Chameleon-like, flexible surfaces
- Polymer FET's

1.1 Applications of Electroactive Polymers

Applications that appear to have the greatest potential for Defense applications fall into two main categories, as shown in Table I. It is important to note that, at least in the authors' opinion, the interesting applications of EAPs do not arise from electroactive properties alone. Though these properties are interesting in and of themselves, there are quite often inorganic counterparts that have similar or even superior properties and usually are more mature. Rather, the uniqueness of these materials for applications arises from the combination of their electroactive properties with the more traditional properties of polymers. Specifically, polymers can be load bearing, easily formed into films and fibers, they are flexible, blendable with other materials and, one hopes, can be produced at relatively low cost. As will be seen, actuation and sensing is a primary example of this combination of electroactive and structural properties. However, even in the second category of applications shown in Table I, the polymeric structure of the material is a critical aspect.

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A brief description of two of the EAP electro-optic applications will serve as examples. The first is the use of the light emitting properties of EAP materials to form flexible LEDs. Dow Chemical is currently supported by DARPA to examine a new family of polymers that exhibit high brightness, and high efficiency at low voltage. Dow has been able to "tune" their polymer system to get EAPs that emit from blue through to red. Though many of the details of this effort are proprietary, there has been some very promising data reported.[8,9] Figure 1 shows some current results for the Dow green emitting polymer system. Once again, there may be inorganic approaches that are more efficient at producing light, but the polymer LEDs potentially have the advantage of being fabricated into flexible films. This flexibility will have obvious payoff to Defense systems in terms of conformal displays or coverings that can change color in a chameleon-like fashion.

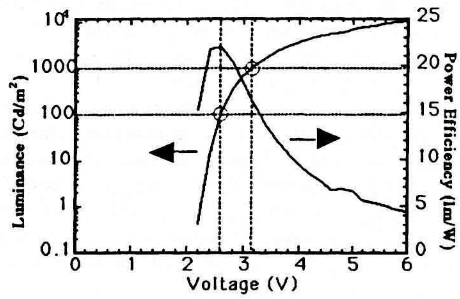

Figure 1. Results on the Dow Green LEP
For 100cd/sqm, efficiency = 21.8 lm/W @ 2.6V
For 1000cd/sqm, efficiency = 16.2 lm/W @ 3.1V

In another effort with Uniax and Raytheon Infrared Center of Excellence (RIRCOE), EAPs are being developed to usher in a new concept for image signal processing. Under this effort, layers of conducting polymers (polyanaline) are being used to form an active resistive network that can be used for analog spatial filtering. Again, specific details are proprietary, but the general concept has been published.[10]

In both of these examples, the primary focus is on the electronic properties of the polymer, but its physical properties are what provides the advantage. This is true to even a greater extent when one considers the use of EAPs as actuators.

2.0 ELECTROACTIVE POLYMER ACTUATION CONCEPTS

This section will briefly discuss the different types of EAP actuators along with some of their limitations. As stated in the Introduction, numerous publications have addressed the basic mechanisms involved in polymer actuators.

In a majority of EAP actuators, the actuation mechanism is based on the movement of an ionic species either in or out of a polymer network. Different types of EAP actuators can be characterized as either gels, ionic polymer metal composites (IPMC) (also called perfluorinated ion-exchange membrane platinum (PIEP)), or conductive polymers.

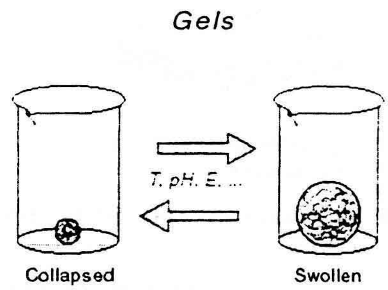

Figure 2. Polymer gel in a solvent

Gels are crosslinked polymer networks in a solvent. The most common gel actuator is activated by changes in pH (other forms of stimuli can cause the gel to react as well;e.g., heat, light, electrical) that in turn causes ions to move into or out of the polymer structure, thus causing it to swell or contract (Figure 2). This mechanism is characterized by very large volume changes, as much as 1000 fold has been reported.[3] The amount of volume change that can be generated in a gel is directly related to its crosslink density. Gels that have a low crosslink density display large volume change; however the low crosslinking produces a low-modulus gel. This low modulus affects the amount of work that can be generated by the polymer gel. Gels that have a high crosslink density show smaller displacement capability but have a high modulus, and therefore a high capacity for work. The gel actuators have two drawbacks: first, the actuation mechanism is based on ion-diffusion, its speed is transport limited and tends to be low; second, these systems require aqueous solutions for operation.

Ionic membrane polymers also rely on transport of ions. These polymer systems are made of an ion conducting membrane material, such as Nafion, that is plated with metal electrodes (for example, platinum). One popular system is the ion-exchange polymer metal composite (IPMC) actuator.[4,5] By applying an electric field to the membrane, ions can be moved from one surface (electrode) to the other, causing the membrane to move. While the actual mechanism is not perfectly understood, it appears that the ion mobility causes expansion of one side of the material and a commensurate contraction of the other. Because the ions are moving within the material, transport is more localized than in polymer gels. Again, the mechanism is diffusion limited and requires an aqueous solution. The hope for these materials is that they can be sealed and, more importantly, that their response time can be improved (possibly by controlling the diffusion distance necessary for actuation). While the IPMC actuators are stiffer than gel actuators, the IPMC materials demonstrated to date tend to be very soft, and thus may have limitations in work-performing ability.

Conducting polymers are similar in principle to the IPMCs and gels in that ion movement causes a dimensional change in the material. Conduction in these polymers is based on incorporating a dopant species (anion or cation) into the polymer network.[1,6] These dopant species modify the polymer's electrical as well as its mechanical properties. Furthermore, by applying an electrochemical potential to the polymer, dopant insertion and deinsertion can occur. This movement of ions in and out of the polymer network leads to dimensional changes that can be used for actuation. As in the above systems, conducting polymers require an anode, cathode, and an electrolyte. The electrodes can be fabricated out of the conducting polymer material, making the actuator components chemically and mechanically compatible.

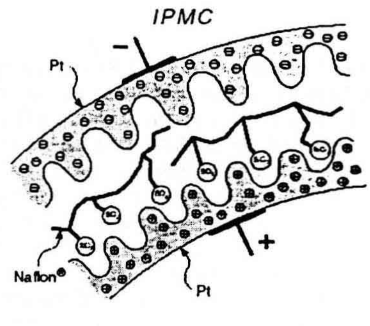

Figure 3. Showing the microstructure of IPMC actuator

Electrostrictive polymers come in two forms. The first form is an actuator based on electrostriction of a polymer dielectric sandwiched between two compliant electrodes.[11] At high electric fields, a large electrostatic force is generated between the electrodes which compresses the dielectric material. Since the materials used to build these actuators are compliant, the actuators can be rolled into cylindrical shapes to provide axial displacements. Electrostrictive actuators based on this approach have demonstrated very fast response rates. However, these actuators require high voltages to operate, which causes integration problems at the system level. Another form of actuation is based on electrostrictive polymers that function on a phase transition principle. Penn State has been engineering poly(vinylidene difluoride-co-trifluouoethylene (P(VDF-TrFE)) co-polymers that exhibit improved strain capability over existing EAPs.[7] The actuation properties of these co-polymers are based on a phase transition (ferroelectric to paraelectric) that these materials undergo. This phase transition leads to a large lattice change within the material which generates large volume changes. Initial data on the P(VDF-TrFE) actuators show a 4% strain capability with <15MPa stress generation.

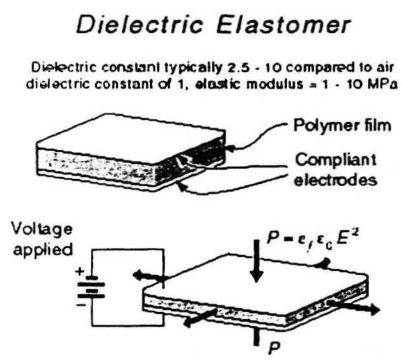

Figure 4. Illustrates the electrostrictive polymer actuator

3.0 THE CHALLENGE FOR EAP ACTUATORS

From the onset, it is valid to ask why one should investigate polymer-based actuators when there is a plethora of other actuator technologies already being used in device designs, and polymer actuators are in their infancy. In short, where is the niche for this class of actuators that would warrant major efforts to develop them?

To answer this question, one needs to examine the performance of existing actuator technologies and to make a general comparison to electroactive polymer systems under development. In examining the actuator characteristics of existing systems, a set of performance metrics can be generated to guide the development of EAP actuators. Established technologies consist of electromagnetic, pneumatic, and hydraulic actuators, each delivering a varying degree of power/mass and force/mass performance. Newer actuator technologies are emerging and include piezoelectric ceramics, magnetostrictive materials, and shape memory alloys. For reasons that will shortly become clear, mammalian muscle is also included in this discussion.

3.1 Comparison of Actuation Technologies

When considering actuation systems for robotics (macro, micro and nano), autonomous vehicles, and general gross and fine actuation needs, it is important to realize that the actuation requirements can and will dominate the overall mechanical design (system level). Therefore, it is difficult to establish the "best" characteristics for an actuation system without considering the specific application. That said, there are several characteristic performance metrics that designers can use to evaluate and compare actuation performance.

The first, shown in Figure 5, is stress versus strain for various actuators. Included in this graph is a set of force density curves.[c] (Essentially this chart shows the force that an actuator can apply, for a given strain). In examining the stress versus strain properties of various actuators, it can be seen that the actuators providing the largest displacements exhibit the lowest stress. Likewise, the actuators that have a large stress capability have relatively low displacement ability. Shape memory alloys (SMA) and hydraulic actuators demonstrate large stress and strain capability. However, SMAs are mechanically inefficient, due to poor conversion of thermal energy into mechanical energy, approximately 2-3%.[12] Hydraulic actuators provide impressive performance and have been extensively implemented in robotic designs. One major drawback with hydraulic systems is the large overhead (pumps, piping, support structure) associated with them that impacts their applicability for small scale devices.

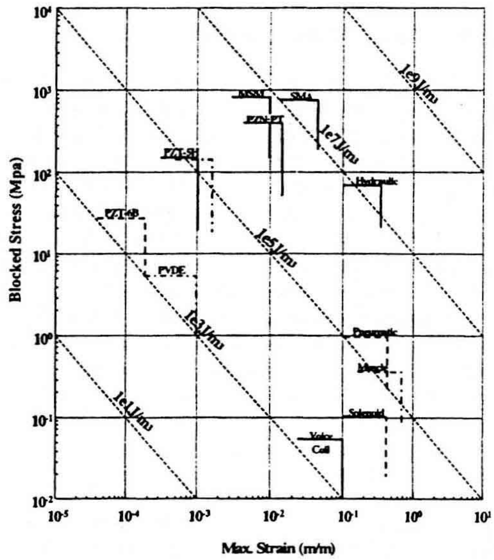

Figure 5. Stress vs. Strain for various actuator technologies (Included are force density curves)

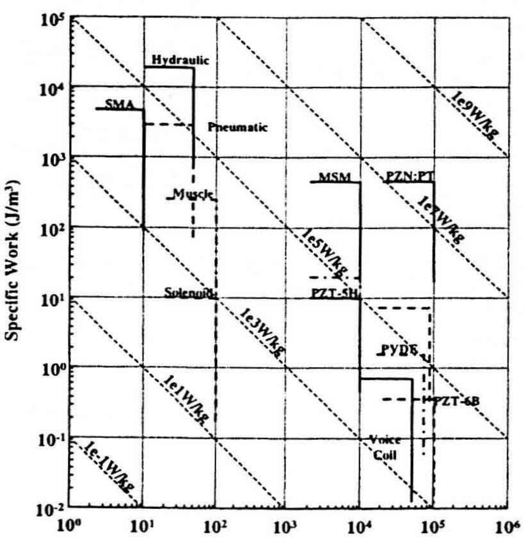

Figure 6. Work vs. Frequency for various actuator technologies (included are power/mass curves)

Another important metric of an actuator is its ability to do work coupled with the rate over which that work can be done, i.e., power. There are numerous ways to examine actuator parameters and, of course, the ultimate performance that matters is at the systems level. Figure 6, which shows the relationship between specific work and actuation frequency (bandwidth) for different types of actuators, is a reasonable representation of performance metrics at the sub-system level.[a] Included in Figure 6 are power/mass curves for comparing actuators that have different bandwidths of specific work capability. In addition, this chart indicates that many actuators that have a high specific work capability also have a limited bandwidth. Similarly, actuators with high bandwidth have a tendency to exhibit low specific work properties.

From this brief analysis, it is clear that there is a wide range of actuator concepts that span a very large "performance space." Based on that, it is apparent that the promise of any new actuator concept has to be based on more than just one performance metric. This is the case with EAP actuators.

Currently, robotic platform and a range of other actuation-based devices use piezoelectric actuation, motors, gears and pulleys. However, at least from a Defense interest point of view, there appears to be a significant advantage to develop

[c] Chart has been generated by Defense Science Research Council for DARPA (unpublished)

actuators that emulate biological functions, e.g., swimming with the stealth of a lamprey,[d] or emulating the hovering ability of an insect. These advantages appear to be especially important as one builds smaller and smaller devices, something that nature is obviously very good at. In those cases, it is not clear that conventional actuation schemes will suffice. What is really needed are actuation schemes that are soft and flexible, allowing easy integration into bio-inspired devices. Of the possible actuation technologies, only those based on polymers appear to have a chance to fulfill this need. It is the authors' opinion that their promise lies in two related aspects: first, EAP's ability to emulate the function of natural muscles; second EAPs are mechanically simple, allowing them to be used for microactuation.

3.2 Quintessential Actuator – Natural Muscle

Table II Characteristics of Natural Muscle

Specific Energy	100-500 J/kg
Specific Work	~ 1 kW/kg
Frequency Response	< 500 Hz
Elongation	>40%

Many robotic designs are bio-inspired. We marvel at the mechanical systems found in nature, and realize that mammalian muscle is an actuation system that has impressive attributes that include, self healing and scalability. It is amazing that skeletal muscles, across all species of mammals, have the same structure. The difference between our muscles and those of the elephant is in the muscle bundle make-up --- the elephant has many more muscle fibers per bundle than found in human muscles. These observations have lead many investigators to seek an actuation system that mimics the natural fiber architecture found in mammals. It is this approach that makes polymers attractive for actuators. The flexibility in manufacturing polymer fibers, and their intrinsic properties for actuation and sensing, affords us the opportunity to engineer actuators that imitate nature. Table II depicts the target that natural muscle presents for the EAP actuator designer. As a specific example, the muscle of a dragonfly muscles operate at a frequency of 30-40Hz with a specific work of about 60-100 W/kg.[13]

3.3 Micro Actuation:

A very good discussion on microactuators (i.e., actuators of size ~1mm^3) can be found in Fearing.[14] This paper reviews the fundamental performance limitations encountered when scaling down actuators for mm-scale operation. In the macro-robotic regime, figures of actuation merit are in terms of power/mass and force/mass parameters. However, when the scale for the robotic actuator approaches the mm range, then the overhead penalty (power supplies, pumps, fixtures, ect.) of these macro-actuator may be too great, and system power density may become a more discriminating metric. Fearing claims that for micro-robotic applications, one should consider actuators that have reasonable speed, high force, and large displacement capability. To further illustrate his point, Fearing calculates the power density needed for a swimming, running and flying micro-vehicle and concludes that their power density requirements range from 20 W/m to 2 x 10^3 W/m. In addition, he shows how for selected actuators their power density decreases with decreasing size. It is the authors' opinion that this makes EAP actuators an ideal candidate for such small systems.

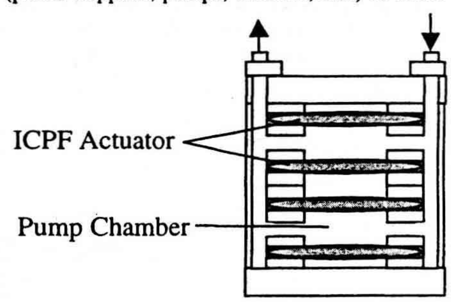

Figure 7. Micropump utilizing EAP polymers, designed and built by Gou.

Knowing the target space for EAP actuators is certainly beneficial to the development of the materials themselves. It is not reasonable and not even useful to try to have EAPs compete with other actuation concepts in applications for which they are ill-suited. However a serious question arises about whether the promise of EAP actuators can live up to the needs even in these limited, albeit important applications. This is the thrust of the remainder of the paper.

[d] The lamprey swims by "corkscrewing" through the water, eliminating the wake, one of the major sources for detecting undersea vehicles.