Paper #2001-1492

Electroactive Polymers as Artificial Muscles – Reality and Challenges

Yoseph Bar-Cohen

NDEAA Technologies, JPL/Caltech, Pasadena, CA

yosi@jpl.nasa.gov, http://ndeaa.jpl.nasa.gov

ABSTRACT

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 changed the potential capability and paradigms of 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. Even though the actuation force of existing EAP materials and their robustness require further improvement, there has already been a series of reported successes. The successful applications that were demonstrated include catheter steering element, miniature manipulator, dust-wiper, miniature robotic arm, and grippers. 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. 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. This paper reviews the current efforts and the expectations for the future.

INTRODUCTION

During the last ten years, new polymers have emerged that respond to electrical stimulation with a significantly shape or size change and this progress has added an important capability to these materials. This capability of the new electroactive polymers (EAP) attracted the attention of engineers and scientists from many different disciplines. Since these materials behave similar to biological muscles, they have acquired the moniker "artificial muscles" [Bar-Cohen, 2001]. 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. In the foreseeable future, robotic mechanisms actuated by EAPs will enable engineers to create devices previously imaginable only in science fiction.

For several decades, it has been known that certain types of polymers can change shape in response to electrical stimulation. Initially, these EAP materials were capable of inducing only a relatively small strain. However, since the beginning of the 1990s, a series of new EAP materials has been developed that can induce large strains leading to a great change in the view of the capability and potential of these materials. Generally, EAPs can induce strains that are as high as two orders of magnitude greater than the striction-limited, rigid and fragile electroactive ceramics (EAC). Further, EAP materials are superior to shape memory alloys (SMA) in higher response speed, lower density, and greater resilience. The current limitations of EAP materials that include low actuation force, mechanical energy density and robustness are limiting the scope of their practical application.

In recognition of the need for international cooperation among the developers, users, and potential sponsors, the author organized the first EAP Conference on March 1-2, 1999, though SPIE International as part of the Smart Structures and Materials Symposium [Bar-Cohen, 1999]. This conference was held in Newport Beach, California, USA and was the largest ever on this subject, marking an important milestone and turning the spotlight onto these emerging materials and their potential. Following this success, a Materials Research Society (MRS) conference was initiated to address fundamental issues related to the material science of EAP [Zhang, et al, 1999]. The SPIE conferences are now organized annually and have been steadily growing in number of presentations and attendees. Currently, there is a website that archives related information and 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 issued electronically (http://ndeaa.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 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 (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, 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.

FIGURE 1: Grand challenge for the development of EAP actuated robotics

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 that was charged and discharged with fixed end and a mass attached to the free end [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, electrical excitation is only one of the stimulator types that can induce elastic deformation in polymers. Other activation mechanisms include chemical [Kuhn, et al, 1950; and Otero, et al, 1995], thermal [Li, et al, 1999], pneumatic [Chou and Hannaford, 1996], optical [van der Veen & Prins, 1971], and magnetic [Zrinyi, et al, 1997].

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 [Steinberg, et al, 1966]. 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 [Bar-Cohen, et al, 1996; and Zhang, et al, 1998], 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 100% have emerged [Pelrine, et al, 1998].

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

Generally, EAP can be divided into two major categories based on their activation mechanism including: ionic and electronic (Table 1). 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.

NON-ELECTRICAL MECHANICALLY ACTIVATED POLYMERS (NEMAP)

There are many polymers that exhibit volume or shape change in response 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:

- Chemically Activated [Katchalsky, 1949; and Schreyer, et al, 2000]
- Shape Memory Polymers [Osada and Matsuda, 1995; & Sokolowski, 1999]
- Inflatable Structures, including McKibben Muscle [Chou and Hannaford, 1996]
- Light Activated Polymers [Aviram, 1978; Smets [1995; and Juodkazis, et al., 2000]
- Magnetically Activated Polymers [Zrinyi, et al, 1999]
- Thermally Activated Gels [Hirokawa and Tanaka, 1984; Ito 1990; Urry, et al, 1996; de Rossi, et al, 1992].

ELECTROACTIVE POLYMERS (EAP)

Polymers that exhibit shape change in response to electrical stimulation can be divided into two distinct groups: electronic (driven by electric field or Coulomb forces) and ionic (involving mobility or diffusion of ions).

ELECTRIC EAP
Ferroelectric Polymers

Piezoelectricity was discovered in 1880 by Pierre and Paul-Jacques Curie, who found that when certain types of crystals are compressed (e.g., quartz, tourmaline, and Rochelle salt), along certain axes, a voltage is produced on the surface of the crystal. The year afterward, they observed the reverse effect that upon the application of an electric current these crystals sustain an elongation. Piezoelectricity is found only in noncentro-symmetric materials and the phenomenon is called ferroelectricity when a nonconducting crystal, or dielectric material exhibits spontaneous electric polarization. Poly(vinylidene fluoride), also known as PVDF or PVF2, and its copolymers are the most widely exploited ferroelectric polymers [Bar-Cohen, et al, 1996]. These polymers are partly crystalline, with an inactive amorphous phase, having a Young's modulus near 1-10 GPa. This relatively high elastic modulus offers high mechanical energy density. A large applied AC field (~200 MV/m) can induce electrostrictive (nonlinear) strains of nearly 2%. Unfortunately, this level of field is dangerously close to dielectric breakdown, and the dielectric hysteresis (loss, heating) is very large. Sen and his coinvestigators [1984] investigated the effect of heavy plasticization (~65 wt. %) of ferroelectric polymers hoping to achieve large strains at reasonable applied fields. However, the plasticizer is also amorphous and inactive, resulting in decreased Young's modulus, permittivity and electrostrictive strains. Zhang [1998] has introduced defects into the crystalline structure using electron radiation to reduce the dielectric loss dramatically in P(VDF-TrFE) copolymer. This permits AC switching with much less generated heat. Extensive structural investigations indicate that high electron irradiation breaks up the coherence polarization domains and transforms the polymer into a nanomaterial consisting of local nanopolar regions in a nonpolar matrix. It is the electric field induced change between non-polar and polar regions that is responsible for a large electrostriction observed in this polymer. As large as 5% electrostrictive strains can be achieved at low frequency drive fields having amplitudes of about 150 V/μm. Furthermore, the polymer has a high elastic modulus (~1 GPa), and the field-induced strain can operate at frequencies higher than 100 kHz, resulting in a very high elastic power density compared with current electroactive polymers. Ferroelectric EAP polymer actuators can be operated in air, vacuum, or water and in a wide temperature range.

Dielectric EAP
Polymers with low elastic stiffness and high dielectric constant can be used to induce large actuation strain by subjecting them to an electrostatic field. This dielectric EAP, also known as electro-statically

stricted polymer (ESSP) actuators, can be represented by a parallel plate capacitor [Pelrine, et al, 1998]. Figure 2 shows a silicone film that in a reference (top) and activated conditions. The right section of the figure shows an EAP actuator that was made using a silicone film that was scrolled to a shape of rope. The rope that is about 2-mm diameter and 3-cm long was demonstrated to lift and drop about 17-gram rock using about 2.5-KV.
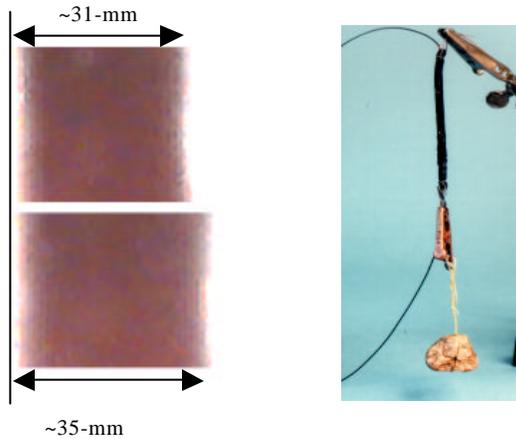

FIGURE 2: Under electro-activation, a dielectric Elastomer with electrodes on both surfaces expands laterally and can be made to operate longitudinally.

The induced strain is proportional to the electric field square, times the dielectric constant in inversely proportional to the elastic modulus. Use of polymers with high dielectric constants and application of high electric fields leads to large forces and strains. To reach the required electric field levels, one needs to either use high voltage and/or employ thin films. Under an electric field the film, is squeezed in the thickness direction causing expansion in the transverse direction. For a pair of electrodes with circular shape, the diameter and thickness changes can be determined using the volume conservation of the film. The above characteristic allows producing longitudinal actuators using dielectric elastomer films with flexible electrodes that appear to act similarly to biological muscles. Dielectric EAP actuators require large electric fields (~100 V/μm) and can induce significant levels of strain (10-200%). Overall, the associated voltages are close to the breakdown strength of the material, and a safety factor that lowers the potential needs to be used. Moreover, the relatively small breakdown strength of air (2-3 V/μm) presents an additional challenge. Recently, SRI International researchers identified a new class of polymers that exhibits an extremely high strain response [Pelrine, et al, 2000]. These acrylic elastomers, (such as 3M™ VHB™ tapes), have produced planar strains of

more than 300% for biaxially symmetric constraints and linear strains of up to 215% for uniaxial constraints.

Electrostrictive Graft Elastomers

In 1998, a graft-elastomer EAP was developed at NASA Langley Research Center exhibiting a large electric field induced strain due to electrostriction [Su, et al, 1999]. This electrostrictive polymer consists of two components, a flexible backbone macromolecule and a grafted polymer that can form crystalline. The grafted crystalline polar phase provides moieties to response to an applied electric field and cross-linking sites for the elastomer system. This material offers high electric field induced strain (~4%), high electro-mechanical power and excellent processability. Combination of the electrostrictive-grafted elastomer with a piezoelectric poly (vinylidene fluoride-trifluoro-ethylene) copolymer yields several compositions of a ferroelectric-electrostrictive molecular composite system. Such combination can be operated both as piezoelectric sensor and as an electrostrictive actuator. Careful selection of the composition allows creating and optimizing the molecular composite system with respect to the electrical, mechanical, and electro-mechanical properties. An example of an electro-activated graft EAP is shown in Figure 3 where a bimorph actuator fabricated using a backing with a passive grafted elastomer. The actuator can bend in both directions under controlled electric field excitation.
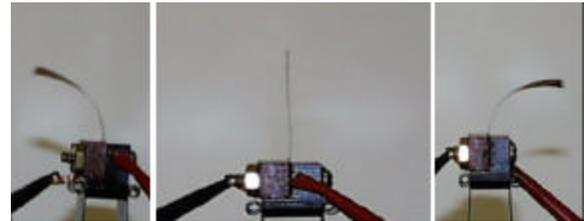

FIGURE 3: An electrostrictive grafted elastomer-based bimorph actuator in an unexcited state (middle), one direction excited state (left), and opposite direction excited state (right). (Courtesy of Ji Su, NASA LaRC, VA)

Electrostrictive Paper

The use of paper as an electrostrictive EAP actuator was demonstrated by Inha University, Korea [Kim, et al, 2000]. Paper is composed of a multitude of discrete particles, mainly of a fibrous nature, which forms a network structure. Since paper is produced in various mechanical processes with chemical additives, it is possible to prepare a paper that has electroactive properties. Such an EAP actuator was prepared by bonding two silver laminated papers with the silver electrodes placed on the ouside surface. When an

electric voltage was applied to the electrodes the actuator produces bending displacement, and its performance depends on the excitation voltages, frequencies, type of adhessive, and the host paper. Studies indicate that the electrostriction effect that is associated with this actuator is the result of electrostatic forces and an intermolecular interaction of the adhesive. The demonstrated actuator is lightweight and simple to fabricate. Various applications are currently being considered including: active sound absorbing materials, flexible speakers, and smart shape control devices.

Electro-Viscoelastic Elastomers

Electro-viscoelastic elastomers represent a family of electroactive polymers that are composites of silicone elastomer and a polar phase. Before crosslinking, in the uncured state, they behave as electro-rheological fluids. An electric field is applied during curing to orient and fix the position of the polar phase in the elastomeric matrix. These materials then remain in the "solid" state but have a shear modulus (both real and imaginary parts) that changes with applied electric field (< 6 V/μm) [Shiga, 1997]. A stronger magneto-rheological effect can also be introduced in an analogous manner and as much as a 50% change in the shear modulus can be induced [Klapcin'ski, et al, 1995; Davis, 1999; & Zrinyi, et al, 1999]. These materials may be used as alternatives to electrorheological fluids for active damping applications.

Liquid Crystal Elastomer (LCE) Materials

Liquid crystal elastomers were pioneered at Alber-Ludwigs Universitat (Freiburg, Germany) [Finkelmann, 1981]. These materials can be used to form an EAP actuator that has piezoelectric characteristics as well as electrically activatable by inducing Joule heating. LCE are composite materials that consist of monodomain nematic liquid crystal elastomers and conductive polymers that are distributed within their network structure [Shahinpoor, 2000]. The actuation mechanism of these materials involves phase transition between nematic and isotropic phases over a period of less than a second. The reverse process is slower, taking about 10-sec, and it requires cooling to cause expansion of the elastomer to its original length. The mechanical properties of LCE materials can be controlled and optimized by effective selection of the liquid crystalline phase, density of crosslinking, flexibility of the polymer backbone, coupling between the backbone and liquid crystal group, and the coupling between the liquid crystal group and the external stimuli [Ratna, 2001], where a rapid contraction appears when the phase transition occurs and the thermo-mechanical behavior is hysteretic.

IONIC EAP

Ionic Polymer Gels (IPG)

Polymer gels can be synthesized to produce strong actuators having the potential of matching the force and energy density of biological muscles. These materials (e.g., polyacrylonitrile) are generally activated by a chemical reactions, changing from an acid to an alkaline environment causes the gel to become dense or swollen, respectively. This reaction can be stimulated electrically as was shown by researchers at the University of Arizona, USA [Liu and Calvert, 2000]. When activated, these gels bend as the cathode side becomes more alkalinic and the anode side more acidic. However, the response of this multilayered gel structure is relatively slow because of the need to diffuse ions through the gel. A significant amount of research and development, as well as applications using ionic gel polymers were explored at the Hokkaido University, Japan. These include electrically induced bending of gels [Osada, et al, 1992] and electrical induced reversible volume change of gel particles [Osada and Kishi, 1989]. Recently, Schreyer and his coinvestigators [2000] used a combination of ionic gel and conductive polymer electrodes to demonstrate an effective EAP actuator.

Ionomeric Polymer-Metal Composites (IPMC)

Ionomeric polymer-metal composite (IPMC) is an EAP that bends in response to an electrical activation (Figure 4) as a result of mobility of cations in the polymer network. In 1992, IPMC was realized to have this electroactive characteristic by three groups of researchers: [Oguro, et al, 1992] in Japan, and [Shahinpoor, 1992] and [Sadeghipour, *et al*, 1992] in the United States. The operation as actuators is the reverse process of the charge storage mechanism associated with fuel cells. A relatively low voltage is required to stimulate bending in IPMC, where the base polymer provides channels for mobility of positive ions in a fixed network of negative ions on interconnected clusters. Two types of base polymers are used to form IPMC: Nafion® (perfluorosulfonate made by DuPont) and Flemion® (perfluorocaboxylate, made by Asahi Glass, Japan. Prior to using these base polymers as EAP, they were widely employed in fuel cells for production of hydrogen (hydrolysis) [Holze and Ahn, 1992]. In order to chemically electrode the polymer films, metal ions (platinum, gold or others) are dispersed throughout the hydrophilic regions of the polymer surface, and are subsequently reduced to the corresponding zero-valence metal atoms. Generally, the ionic content of the IPMC is an important factor in the electromechanical response of these materials [Nemat-Nasser and Li, 2000; & Bar-Cohen, et al, 1999]. Examining the bending response shows that using low voltage (1-10 Volts) induces a large bending at frequencies below 1-Hz, and the displacement

significantly decreases with the increase in frequency. In recent years, the bending response of IPMC was enhanced using Li+ cations that are small and have higher mobility or large tetra-n-butylammonium cations that transports water in a process that is still under studies. The actuation displacement of IPMC was further enhanced using gold metallization as a result of the higher electrode conductivity [Oguro, et al, 1999].
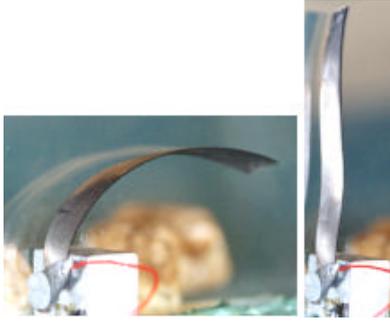

FIGURE 4: IPMC in activated and reference states.

Conductive Polymers (CP)

Conductive polymers typically function via the reversible counter-ion insertion and expulsion that occurs during redox cycling [Otero, et al, 1995]. Oxidation and reduction occur at the electrodes inducing a considerable volume change mainly due to the exchange of ions with an electrolyte. A sandwich of two conductive polymer electrodes (e.g., polypyrrole or polyaniline, or PAN doped in HCl) with an electrolyte between them forms an EAP actuator. When a voltage is applied between the electrodes, oxidation occurs at the anode and reduction at the cathode. Ions (H^+) migrate between the electrolyte and the electrodes to balance the electric charge. Addition of the ions causes swelling of the polymer and conversely their removal results in shrinkage and as a result the sandwich bends. Some of the parameters that affect the response include the thickness of the layers: thinner layers are faster (as fast as 40-Hz) but induced lower force. Since strong shear forces act on the electrolyte layer, attention is needed to protect the material from premature failure. Conductive polymer actuators generally require voltages in the range of 1-5 V, and the speed increases with the voltage having relatively high mechanical energy densities of over 20 J/cm^3 but with low efficiencies at the level of 1% [Otero and Sansiñena, 1998]. In this Figure, a bilayer strip made of 3mg polypyrrole film (PPy) (area = 3 cm^2 and thickness = 6 µm) and an adhesive tape (No volume-change Film, NVC) is shown to lift 1-gram steel ball (about 300 times heavier than the PPy). The strip was activated by 30 mA electric current and is shown after partial oxidation (left), natural state (middle), and partial reduction (right).

Various approaches are being considered to operate this EAP in dry environments where the use of quasi-solid electrolytes and the application of protective coating are some of the alternatives. In recent years, several conductive polymers were reported including polypyrrole, polyethylenedioxythiophene, poly(p-phenylene vinylene)s, polyaniline, and polythiophenes. Complexes between polypyrrole and sulfonated detergents offer relatively good stability in aqueous media, but are relatively soft compared to other conjugated polymers. Most actuators that use conductive polymers exploit voltage controlled swelling to induce bending. Conjugated polymer microactuators were first fabricated at the Linköpings universitet, Sweden, among the devices that were demonstrated included miniature boxes that can be opened and closed [Smela, et al, 1995]. Using this technology a micro-robot was developed and other applications may evolve including surgical tools or robots to assemble other micro-devices in a factory-on-a-desk [Jager, et al, 2000].

Operation of conductive polymers as actuators at the single-molecule level is currently being studied taking advantage of intrinsic electroactive property of individual polymer chains. Researchers at the University of California, Riverside [Marsella and Reid, 1999] used {4n}annulene chemistry as a method of "encoding" actuation into individual polymer chains. It is well known that cyclooctatetraene (a tube-shaped {8}annulene) becomes planar upon oxidation or reduction. During such a process, the distance between carbons 1 and 4 is altered. By utilizing an {8} annulene as a polymer repeat-unit, such redox-induced conformational changes can be translated into a change in the effective monomer length. The effective polymer chain length is ultimately altered causing the alteration of the effective length of the monomer. Thus, a single molecule electromechanical actuator can be enabled.

Carbon Nanotubes (CNT)

In 1999, carbon nanotubes with diamond-like mechanical properties emerged as formal EAP [Baughman, et al, 1999]. The carbon-carbon bond in nanotubes (NT) that are suspended in an electrolyte and the change in bond length are responsible for the actuation mechanism. A network of conjugated bonds connects all carbons and provides a path for the flow of electrons along the bonds. The electrolyte forms an electric double layer with the nanotubes and allows injection of large charges that affect the ionic charge balance between the NT and the electrolyte. The more charges are injected into the bond the larger the dimension change. Removal of electrons causes the nanotubes to carry a net positive charge, which is

spread across all the carbon nuclei causing repulsion between adjacent carbon nuclei and increasing the C-C bond length. Injection of electrons into the bond also causes lengthening of the bond resulting increase in nanotubes diameter and length. These dimension changes are translated into macroscopic movement in the network element of entangled nanotubes and the net result is extension of the CNT.

Considering the mechanical strength and modulus of the individual CNTs and the achievable actuator displacements, this actuator has the potential of providing work per cycle that is higher than any previously reported actuator technologies and of generating much higher mechanical stresses. The material consists of nanometer size tubes and it was shown to induce strains at the range of 1% along the length. The key obstacle to the commercialization of this EAP is it high cost and the difficulty in mass-production of the material.

ElectroRheological Fluids (ERF)

ElectroRheological fluids (ERFs) experience dramatic changes in their viscosity, when subjected to an electric field. These fluids are made from suspensions of an insulating base fluid and particles 0.1 – 100 μm in size. Willis M. Winslow first explained the electrorheological effect in the 1940s using oil dispersions of fine powders [Winslow, 1949]. The electro-rheological effect, sometimes called the *Winslow* effect, is thought to arise from the difference in the dielectric constants of the fluid and particles. In the presence of an electric field, the particles, due to an induced dipole moment, will form chains along the field lines. This induced structure changes the ERF's viscosity, yield stress, and other properties, allowing the ERF to change consistency

from that of a liquid to something that is viscoelastic, such as a gel, with response times to changes in electric fields on the order of milliseconds. A good review of the ERF phenomenon and the theoretical basis for their behavior can be found in [Block and Kelly, 1988]. Control over a fluid's rheological properties offers the promise of new possibilities in engineering for actuation and control of mechanical motion. The ability to control the viscosity and the rapid response of ERF allow simplification of the mechanisms that are involved with hydraulics. Their solid-like properties in the presence of a field can be used to transmit forces over a large range and have found a large number of applications including shock absorbers, active dampers, clutches, adaptive gripping devices, and variable flow pumps.

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 exhibit low force, are far below their efficiency limits, are not robust, and there is no standard commercial material available for consideration in practical applications. The documented EAP materials that induce large strains are driven by many different phenomena [Bar-Cohen, 1999; Bar-Cohen, 2000; and Zhang, et al, 1999]. Each
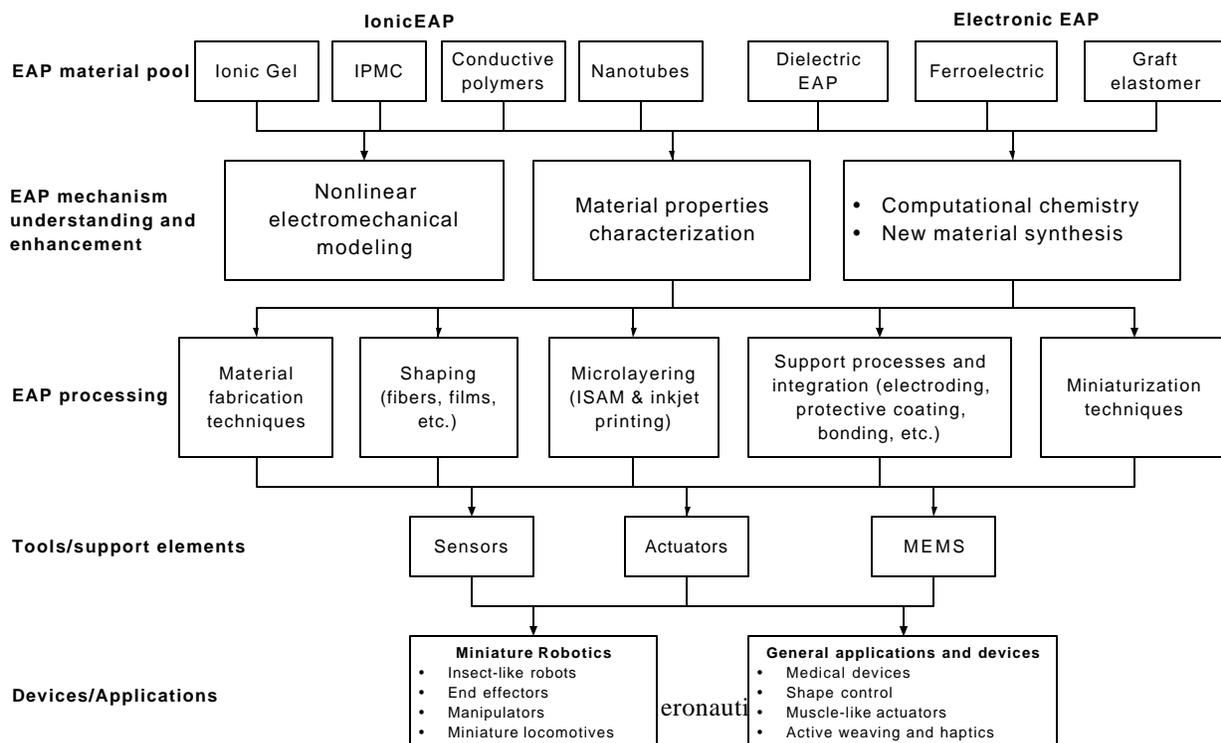
of these materials requires adequate attention to their unique properties and constraints. In order to be able to take these materials from the development phase to use as effective actuators, there is a need to establish an adequate EAP infrastructure. The author's view of this infrastructure and the areas that need development are shown schematically in Figure 5. Effectively addressing the requirements of the EAP infrastructure involves developing adequate understanding of EAP materials' behavior, as well as 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. 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. The development of the infrastructure is a multidisciplinary task and it requires international collaboration.

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 operate biologically inspired mechanisms driven by EAP as artificial muscles is offering capabilities that are currently considered science fiction. The author's arm-wrestling challenge having 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. 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 niche cases, these materials will be used in spite of their current limitations while taking advantage of their uniqueness.

REFERENCE

Aviram A., "*Mechanophotochemistry*," Macro-molecules, Vol. 11, (1978) p. 1275.

Bar-Cohen Y., T. Xue and S.-S., Lih, "Polymer Piezoelectric Transducers For Ultrasonic NDE," 1st International Internet Workshop on Ultrasonic NDE, Subject: Transducers, organized by R. Diederichs, UTonline Journal, Germany, (Sept. 1996). http://www.ndt.net/article/yosi/yosi.htm

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., S. Leary, K. Oguro, S. Tadokoro, J. Harrison, J. Smith and J. Su, "Challenges to the Transition of IPMC Artificial Muscle Actuators to Practical Application," Proceedings of the 1999 Fall MRS Symposium, ISBN 1-55899-508-0, Vol. 600, (1999).

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 (2000) pp 1-360.

Bar-Cohen Y. (Ed.), "Electroactive Polymer (EAP) Actuators as Artificial Muscles - Reality, Potential and Challenges," SPIE Press, Expected to be published at the end of February 2001 (In print).

Baughman R.H., C. Cui, A. A. Zakhidov, Z. Iqbal, J. N. Basrisci, G. M. Spinks, G. G. Wallace, A. Mazzoldi, D. de Rossi, A. G. Rinzler, O. Jaschinski, S. Roth and M. Kertesz, "Carbon Nanotune Actuators," Science, Vol. 284, (1999) pp. 1340-1344.

Block, H. and Kelly, J. P., "Electro-Rheology*, Journal of Physics, D: Applied Physics,* Vol. 21, (1988) pp. 1661-1677.

Brock, D. L., "Review of Artificial Muscle Based on Contractile Polymers," MIT AI Memo No. 1330 (1991),

Chou, C. P. and B. Hannaford, "Static and Dynamic Characteristics of McKibben Pneumatic Artificial Muscles. Proceedings of the IEEE International Conference on Robotics and Automation," San Diego, CA, May 8-13, 1994, 1:281-286.

de Rossi, D., M. Suzuki, Y. Osada, and P. Morasso, "Pseudomuscular gel actuators for advanced robotics," J. of Intelligent Material Systems and Structures, Vol. 3, (1992) pp.75-95.

Eguchi M., Phil. Mag., Vol. 49, (1925)

Finkelmann H., H.J. Kock and G. Rehage, "Investigations on Liquid Crystalline Silozanes: 3. Liquid Crystalline Elastomer – A New Type of Liquid Crystalline Material," Makromolecular Chemistry, Rapid Communications, Vol. 2 (1981), p. 317.

Hirokawa Y. and T. Tanaka, "Volume Transition in nonionic gel," J. Chem. Physics, Vol. 81, (1984), p. 6379.

Holme N.C.R., L. Nikolava, S. Hvilsted, P.H. Rasmussen, R.H. Berg, P.S. Ramanujam, "Optically induced surface relief phenomena in azobenzene polymers," Appled Physics Letters, Vol. 74, (1999), p. 519.

Holze R., and J. C. Ahn, "Advances in the use of Perfluorinated Cation-Exchange Membranes in Integrated Water Electrolysis and Hydrogen - Oxygen Fuel Systems," J. Membrane Sci., Vol. 73, No. 1, pp. 87-97 (1992).

Ito S., "Phase transition of aqueous solution of poly(N-alkoxyacrylamide) derivatives-effect of side chain structure," Koubunshu, Vol. 47, No. 6 (1990), p. 467.

Jager E. W. H., O. Inganäs, and I. Lundström, "Microrobots for Micrometer-Size Objects in Aqueous Media: Potential Tools for Single Cell Manipulation," Science, Vol. 288 (2000) pp. 2335-

Juodkazis S., N. Mukai, R. Wakaki, A. Yamaguchi, S. Matsuo and H. Misawa,, "Reversible phase transitions in polymer gels induced by radiation forces," Nature Vol. 408, No. 6809 (2000) pp. 178-180.

Katchalsky, A., "Rapid Swelling and Deswelling of Reversible Gels of Polymeric Acids by Ionization", Experientia, Vol. V, (1949), pp 319-320.

Kim J., J.-Y. Kim and S.-J. Choe, "Electro-Active Papers: Its Possibility as Actuators," Y. Bar-Cohen Y., (Ed.), Proceedings of the SPIE's EAPAD Conf., part of the 7th Annual International Symposium on Smart Structures and Materials, Vol. 3987, ISBN 0-8194-3605-4 (2000) pp 203-209.

Klapcin´ski T., A. Galeski and M. Kryszewski, Polyacrylamide "Gels Filled with Ferromagnetic Anisotropic powder: A Model of a Magnetochemical Device," J. Appl. Polymer Science, Vol. 58, (1995) p. 1007.

Kuhn W., B. Hargitay, A. Katchalsky, and H. Eisenburg, "Reversible dilatation and contraction by changing the state of ionization of high-polymer acid networks," Nature, Vol. 165 (1950), pp. 514-516.

Li F. K., W. Zhu, X. Zhang, C. T. Zhao, and M. Xu, "Shape memory effect of ethylene-vinyl acetate copolymers," J. Appl. Polym. Sci., Vol. 71, No. 7 (1999), pp. 1063-1070.

Liu Z. and P. Calvert, "Multilayer Hydrogels and Muscle-Like Actuators," Advanced Materials, Vol. 12, No. 4 (2000), pp. 288-291.

Marsella M. J., and R. J Reid, Macromolecules, Vol. 32, (1999), 5982-5984.

Nemat-Nasser, S., and Li, J. Y. "Electromechanical response of ionic polymer-metal composites", J. Applied Physics, Vol. 87, No. 7, (2000), pp. 3321-3331.

Oguro K., N. Fujiwara, K. Asaka, K. Onishi, and S. Sewa, "Polymer electrolyte actuator with gold electrodes," Proceedings of the SPIE's 6th Annual International Symposium on Smart Structures and Materials, Vol. 3669, ISBN 0-8194-3143-5, (1999), pp. 64-71.

Oguro, K., Y. Kawami and H. Takenaka, "Bending of an Ion-Conducting Polymer Film-Electrode Composite by an Electric Stimulus at Low Voltage," Trans. Journal of Micromachine Society, Vol. 5, (1992) pp. 27-30.

Osada Y., A. Matsuda, "Shape memory in hydrogels", Nature, Vol. 376 (1995), p. 219

Osada Y., and M. Hasebe, "Electrically Activated Mechanochemical Devices Using Polyelectrolyte Gels, Chemistry Letters, 1285-1288, 1985.

Osada Y., and R. Kishi, "Reversible Volume Change of Microparticles in an Electric Field", J. Chem. Soc., 85, 665-662, 1989.

Osada, Y., H. Okuzaki, and H. Hori, "A polymer gel with electrically driven motility," Nature Vol. 355, (1992), pp. 242-244.

Otero T. F., and Sansiñena, J. M., "Soft and wet conducting polymers for artificial muscles," Advanced Materials 10 (6), (1998) pp. 491-494.

Otero T. F., H. Grande, J. Rodriguez, "A new model for electrochemical oxidation of polypyrrole under conformational relaxation control," J. Electroanal. Chem., Vol. 394 (1995), pp. 211-216.

Pelrine R., R. Kornbluh, and J. P. Joseph, "Electrostriction of polymer dielectrics with compliant electrodes as a means of actuation," Sensor Actuat. A, Vol. 64 (1998), p.77-85.

Pelrine R., R. Kornbluh, Q. Pei, and J. Joseph, "High Speed Electrically Actuated Elastomers With Strain Greater Than 100%," Science, Vol. 287, (2000) pp. 836-839.

Ratna B. R., "Liquid Crystalline Elastomers as Artificial Muscles: Role of Side Chain – Backbone Coupling," To be published in the Proceedings of the SPIE's 8th Annual International Symposium on Smart Structures and Materials, EAPAD Conf. (2001).

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).

Sadeghipour, K., R. Salomon, and S. Neogi, "Development of a Novel Electrochemically Active Membrane and 'Smart' Material Based Vibration Sensor/Damper," *Smart Materials and Structures*, (1992) 172-179.

Schreyer H. B., N. Gebhart, K. J. Kim, and M. Shahinpoor, "Electric activation of artificial muscles containing polyacrylonitrile gel fibers," *Biomacromolecules J*., ACS Publications, Vol. 1, (2000), pp. 642-647

Sen A., Scheinbeim, J.I., and Newman, B.A., "The effect of platicizer on the polarization of poly(vinylidene fluoride) films," *J. Appl. Phys.,* Vol.56, No.9, pp.2433-2439 (1984).

Shahinpoor M., "Elastically-Activated Artificial Muscles Made with Liquid Crystal Elastomers," Y. Bar-Cohen, (Ed.), Proceedings of the SPIE's 7th Annual International Symposium on Smart Structures and Materials, EAPAD Conf. Vol. 3987, ISBN 0-8194-3605-4 (2000) pp. 187-192.

Shahinpoor, M., "Conceptual Design, Kinematics and Dynamics of Swimming Robotic Structures using Ionic Polymeric Gel Muscles," *Smart Materials and Structures*, Vol. 1, No. 1 (1992) pp. 91-94.

Shiga, T. "Deformation and viscoelastic behavior of polymer gels in electric fields," *Adv. Polym. Sci.,* Vol. 134, pp. 131-163 (1997).

Smela E., O. Inganäs, and I. Lundström, "Controlled folding of micrometer-size structures," Science, Vol. 268 (1995) pp. 1735-1738.

Smets G., "New developments in photochromic polymers", J. Polymers Science, Polymers Chemistry, Vol. 13 (1975) p. 2223.

Sokolowski W. M., A. B. Chmielewski, and S. Hayashi, "Cold hibernated elastic memory (CHEM) self-deployable structures," Y. Bar-Cohen, (Ed.), Proceedings of the SPIE's 6th Annual International Symposium on Smart Structures and Materials, Vol. 3669, ISBN 0-8194-3143-5, (1999) pp. 179-185.

Steinberg I. Z., A. Oplatka, and A. Katchalsky, "Mechanochemical engines," *Nature*, vol. 210, (1966) pp.568-571.

Su J., J. S. Harrison, T. St. Clair, Y. Bar-Cohen, and S. Leary, " Electrostrictive Graft Elastomers and Applications," ISBN 1-55899-508-0, MRS Symposium Proceedings, Vol. 600, Warrendale, PA, (1999) pp 131-136.

Urry D.W., L.C. Hayes, and S.Q. Peng, "Design for Advanced Materials by the ΔT_t-Mechanism," in Smart Structures and Materials 1996: Smart Materials Technologies and Biomimetics, Andrew Crowson (Ed.), Proc. SPIE 2716, (1996) pp. 343-346

van der Veen G. and W. Prins, Phys. Sci., Vol. 230 (1971) , pp. 70.

Winslow, W. M., "Induced Fibrillation of Suspensions," *Journal of Applied Physics*, Vol. 20, (1949), pp. 1137.

Woojin L, "Polymer Gel Based Actuator: Dynamic model of gel for real time control," Ph.D. Thesis, Massachusetts Institute of Technology (1996)

Zhang Q. M., V. Bharti, and X. Zhao, "Giant electrostriction and relaxor ferroelectric behavior in electron-irradiated poly(vinylidene fluoride-trifluorethylene) copolymer," *Science*, Vol. 280, pp.2101-2104 (1998).

Zhang Q., Electroactive Polymers with High Electrostrictive Strain and Elastic Power Density," WW-EAP Newsletter, Vol. 1, No. 2 (1999) p. 12.

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.

Zrinyi M., D. Szabo and J. Feher, "Comparative Studies of Electro- and Magnetic Field Sensitive Polymer Gels," Y. Bar-Cohen, (Ed.), Proceedings of the SPIE's 6th Annual International Symposium on Smart Structures and Materials, EAPAD Conf. Vol. 3669, ISBN 0-8194-3143-5, (1999) pp. 406-413.

Zrinyi M., L. Barsi, D. Szabo, and H. G. Kilian, "Direct observation of abrupt shape transition in ferrogels induced by nonuniform magnetic field," *J. Chem. Phys.,* Vol. 106, No. 13 (1997), pp. 5685-5