EAP ACTUATORS FOR MICRO ROBOTICS: a NEW PERSPECTIVE

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Abstract. *Actuation devices are used for many mechanisms which are present in our daily life and there is an increasing need to reduce their size, mass and power consumption as well as to cut their cost. There are many types of actuators, such as electro ceramics (piezoelectric and electrostrictive), shape memory alloy, shape memory polymer, magnetostrictive, electromagnetic, electro active polymer, and others. Potentially, electro active polymers, EAPs, are characterized for low-mass, low-power, inexpensive miniature muscle actuators which are superior to the widely used actuators. Under electrical excitation, EAPs, contract and thus form a basis for muscle actuators.* T*hese materials as actuators to drive several devices that are being considered or developed are applicable to mechanisms, robotics, toys, animatronics, human-machine interface, planetary applications, medical applications, liquid and gases flow control and controlled weaving. This paper focuses on a comparison between EAPs and the other actuators technologies. It shows that, while lagging in force delivering capability, these materials are superior in mass, power consumption and displacement levels. In addition, it will show a new application for the bioengineering field: EAP robots for diagnostics and microsurgery.*

Keywords*: actuators, electro active polymer, bioengineering, electro active polymer muscle actuators.*

1. Introduction

The recent introduction of polymers that induce large strain under electrical activation led to their consideration as potential actuators. The level of induce strain can be as high as two orders of magnitude greater than the striction – limited, rigid and fragile Electro Active Ceramics (EAC) actuators (piezoelectric and eletrostrictive). Also, they are superior to Shape Memory Alloys (SMA) in their spectral response, lower density, and resilience. Shape memory polymers are material which sustain a volume change of over 40 times using pressure and heat to stow it in a compact form, whereas a temperature of 55°C causes a recovery of the pre-pressed shape (Sokolowski *et al*, 1999). 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 table electrically (Bar-Cohen, 2000). On the other hands, EAP materials reach their elastic limit at lower stress levels compared to EAC, and their actuation stress levels compared to EAC, and their actuation stress falls for shorter than EAC and SMA actuators. In Tab. 1, a comparison between EAP and other actuators technologies is shown and it is easy to see the properties in which EAP offer superior capability.

Table 1. Comparison of the properties of EAP, SMA and EAC.

Property	EAP	SMA	EAC
Actuation displacement	Over 300%	8% short fatigue life	0.1 – 0.3%
Force MPa	0.1 - 40	200	30 – 40
Reaction speed	μsec to sec	μsec to min	μsec to sec
Density	1 – 2.5 g/cc	5 – 6 g/cc	6 – 8 g/cc
Drive voltage	1 – 7 V	5 Volt	50 – 800 V
Power consumption	m watts	watts	watts
Fracture toughness	Resilient, elastic	Resilient, elastic	fragile

The most attractive feature of EAPs is their ability to emulate biological muscles offering resilience, toughness, large actuation strain and different vibration damping, This similarity named them an Artifical Muscles (Bar-Cohen, 2001a) 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 it 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.

2. 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).

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).

Generally, the EAPs are divided into two major categories based on their activation mechanism: electronic (driven by electric field or Coulomb forces) and ionic (involving mobility or diffusion of ions) (Bar-Cohen, 2001) (Table 2). The electronic polymers, such as electrostrictive, electrostatic, piezoelectric and ferroelectric require high activation field close to the breakdown level. In contrast, ionic EAP materials, such as gel, polymer-metal composites, conductive polymers and carbon nanotubes require drive voltage as low as 1-5 V. 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 electronic and ionic EAP can be designed geometrically to bend, stretch, or contract.

Table 2. 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 (~150MV/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 EAP's do not hold strain under DC voltage; • Slow response (fraction of a second); • Bending EAP's induce a relatively low actuation force; • In aqueous systems the material sustains hydrolysis at > 1.23V.

2.1 Electronic EAP's

Zhang *et al.* (1998), has observed an exceptionally high electrostrictive response in electron-irradiated poly (vinylidene fluoride-trifluoroethylene) [P (VDF-TrFE)] copolymer. It is the electric-field-induced change between nonpolar and Polar Regions that are responsible for the large electrostriction observed in this polymer. As large 4% electrostrictive strains can be achieved at low frequency drive fields having amplitudes of about 150V/μm. However, the electron-irradiation process is difficult for mass production. His research team is developing acoustic transducers for use in medical imaging equipment, underwater acoustic and stereo speakers.

Dielectric elastomer based EAPs have been under investigation at SRI for the past 10 years. Dielectric elastomer transducers are rubbery polymer materials with compliant electrodes that have a large electromechanical response to an applied electric field. The induced strain is proportional to the square of electric field, multiplied by the dielectric constant and 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. The deformation of the polymer film can be used in many ways to produce muscle-like linear actuation. A linear artificial muscle was made based on an acrylic-film double bow-tie actuator. An acrylic-film rolled actuator was developed and applied to an insect-inspired legged robot. An insect-inspired flapping-wing robot was demonstrated by using four silicon bow-tie actuators.

A graft-elastomer EAP was developed at NASA Langley Research Center (Su *et al.*, 1999a) and it exhibits not only large electric field-induced strain (4%) but also a relatively high mechanical modulus (560 MPa). This electrostrictive polymer consists of two components, a flexible backbone macromolecules and a grafted polymer that can form crystalline. By combining this graft elastomer with a piezoelectric polymer, an electrostrictive-piezoelectric

multifunctional polymer blend system has been developed. Such combination can be operated both as a piezoelectric sensor and as an electrostrictive actuator.

2.1.1. Ferroelectric polymer

Piezoelectricity was discovered in 1880 by Pierre and Paul-Jacques Curie, who realized that when certain types of crystals are compressed (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. The phenomenon is described by a third-rank tensor that is defined by, Eq. (1):

$$d = \left(\frac{\partial D}{\partial T}\right)_E = \left(\frac{\partial S}{\partial E}\right)_T \tag{1}$$

where D is the dielectric displacement, E is the electric field, T is the mechanical stress; and S is the mechanical strain.

Piezoelectricity is found only in noncentro-symmetric 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, and 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. Ferroelectric EAP polymer actuators can be operated in air, vacuum, or water and in a wide temperature range.

2.1.2 Dielectric

Polymer 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). Dielectric EAP actuators require large electric fields (~100 V/μm) and can induce significant levels os strain (10-200%). Overall, the associated voltages are close to the breakdown strength of the material, and a safety factor that lowers the potential is needed. Moreover, the relatively small breakdown strength of air (2-3 V/μm) presents an additional challenge. These acrylic elastomers, (such as 3M^{TM} VHB^{TM} tapes), have produced planar strains of more than 300% for biaxially symmetric constraints and linear strains of up to 215% for unixial constraints. Figure 1 shows a silicone film that in a reference 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.

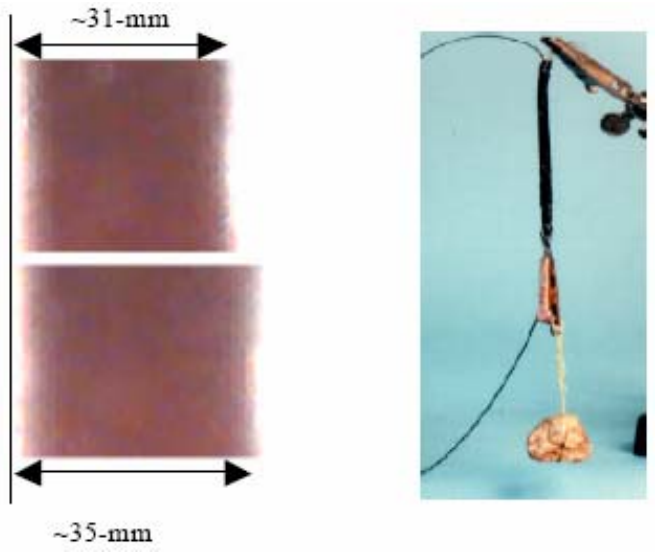

Figure 1. Under electro-activation, a dielectric Elastomer with electrodes on both surfaces expands laterally and can be made to operate longitudinally. (Courtesy of SRI International)

2.1.3 Electrostrictive graft elastomers

In 1998, a graft-elastomer EAP was developed at NASA Langley Research Center that exhibits a large electric-field-induced strain due to electrostriction. 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 respond to an applied electric field and cross-linking sites for the elastomer system. This material offers high electric field induced strain (~4%), high electromechanical power and excellent processability. The combination of the electrostrictive-grafted elastomer with a piezoelectric poly (vinylidene fluoride-trifluoroethylene) 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. A careful selection of the composition allows creating and optimizing the molecular composite system with respect to the electrical, mechanical, and electromechanical properties (Su *et al*, 1999b). An example of an electroactivated graft EAP is shown in "Fig. 2".

Figure 2. 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).

2.1.4 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 form 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 it applied the electrodes the actuator produces bending displacement, and its performance depends on the excitation voltages, frequencies, type of adhesive, 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. Various applications are currently being considered including: active sound absorbing materials, flexible speakers, and smart shape control devices.

2.1.5 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 material then remain in the "solid" state but they have a shear modulus (both real and imaghinary parts) that changes with applied electric field (< 6 V/μm) (Bar-Cohen, 2001b). A stronger magneto-rheological effect can also be introduced in an analogous manner and much as a 50% change in the shear modulus can be induced. These materials may be used as alternatives to eletrorheological fluids for active damping applications.

2.1.6 Liquid crystal elastomer (LCE) materials

Liquid crystal elastomers were pioneered at Alber-Ludwings Universitat (Finkelmann, 1981). These materials can be used to form an EAP actuator that has piezoelectric characteristics and can be electrically activated by inducing Joule heating. 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, which causes 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 cross-linking, 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.

Generally, liquid crystals are supramolecular ordered assemblies and as such have an excellent framework for incorporating anisotropy and functionalities that include response to external stimuli. Slight cross-linking of polymeric liquid crystals show elasticity similar to that of conventional elastomers but with some special properties. In such a

cross-linked polymer, it is possible to create deformations on macroscopic length scales by changing the orientational order of the mesogenic group by external stimuli.

In the nematic phase, the orientational order of the mesogen forces the polymer backbone to be elongated along the average direction of orientation of the mesogens. However, upon heating the isotropic phase, the nematic order is lost thereby allowing the polymer backbone to relax to its coiled conformation. LCEs provide a number of advantages including the possibility of using them in the dry state and the ease to introduce multifunctionality into them.

2.2. Ionic EAP

Ionic polymer gels can be synthesized to produce strong actuators having the potential that matches or is comparable to the force and energy density of biological muscles. Liu and Calvert (2000a) at the University of Arizona have made muscle-like actuators from bilayers of crosslinked polyacrylamide, these gels bend as the cathode side becomes more alkaline and the anode side more acidic. However, the response oh this multilayered gel structure is relatively slow because of the need to diffuse ions through the gel. Nonionic polymer gels containing a dielectric solvent can be made to swell under a dc-electric field with a significant strain.

An Ionomeric polymer-metal composite (IPMC) is a well-known EAP that bends in response to an electrical activation as a result of mobility of cautions in the polymer network (Shahinpoor *et al*, 2000b). A relatively low voltage is required to stimulate bending in IPMC, whereas the base provides channels for mobility of positive ions in a fixed network of negative ions on interconnected clusters. However, the slow response and the need of wetness restrict the applications.

Conducting polymer (CP) typically function via the reversible counter-ion insertion and expulsion that occurs during redox cycling. Most studies have investigated the contractile properties of two CPs, polypyrrole or polyaniline. They have investigated the dimensional changes in the CP polypyrrole. Strains up to 6%, strain rates of 4%/s, power to mass rations of 40 W/kg and forces of up to 34 Pa are achieved. Otero *et al.* (1995) first have investigated bilayer CP actuators. CP actuators based on trilayer have been made by many research groups in Japan, USA and some other countries.

Researchers at the University of Pisa in Italy reported the construction and characterization of a linear actuator prototype made of PANi fibers, a solid polymer electrolyte, and a spiral-shaped copper wire as counter-electrode. Artificial Muscle Research Institute of the University of Mexico is developing a new technique that electrically activates PAN fibers. By making a composite with a conductive medium and polypyrrole an electrical activation of PAN is possible when Conductive Polyacrylonitrile (C-PAN) is placed in a hydrolysis cell (Shahinpoor *et al*., 2000c). Linkopings University in Sweden developed a microrobotic arm with individual controllable hinges for an elbow, a wrist and 2-4 fingers by using CP actuators (Bar-Cohen, 2001c).

2.2.1 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 (polyacrylonitrile) are generally activated by chemical reactions, changing from an acid to an alkaline environment causing the gel to become dense or swollen, respectively. This reaction can be stimulated electrically as it was shown by researchers at the University of Arizona, USA (Liu and Calvert, 2000b). 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 ionoc gel polymers were explored at the Hokkaido University, Japan. These include electrically induced bending of gels and electrical induced reversible volume change of gel particles. Recently, researchers used a combination of ionic gel and conductive polymer electrodes to demonstrate affective EAP actuators (Bar-Cohen, 2001d).

2.2.2 Ionomeric polymer-metal composites (IPMC)

Ionomeric polymer-metal composite (IPMC) “Fig. 3” is an EAP that bends in response to an electrical activation 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 (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) (Bar-Cohen, 2001e). In order to chemically electrode the polymer films, metal ions (platinum, gold or others) are dispersed throughout the hidrophilic 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 and Bar-Cohen *et al*, 1999). Examining the bending response shows that using low voltage (1-10 Volts) it 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 or large tetra-n-lammonium 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).

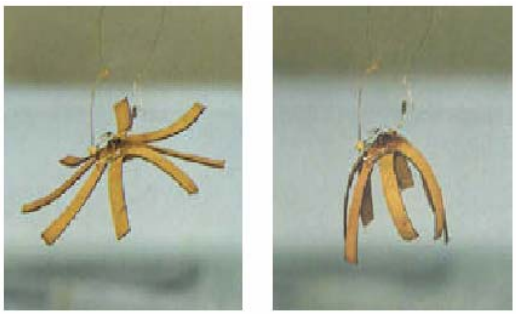

Figure 3. IPMC multi-finger starfish (Courtesy of K. Oguro)

2.2.3 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 (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 thepolymer 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 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% (Bar-Cohen, 2001f). The strip was activated by 30 mA electric current and is shown after partial oxidation (left) and partial reduction (right) “Fig. 4”. 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.

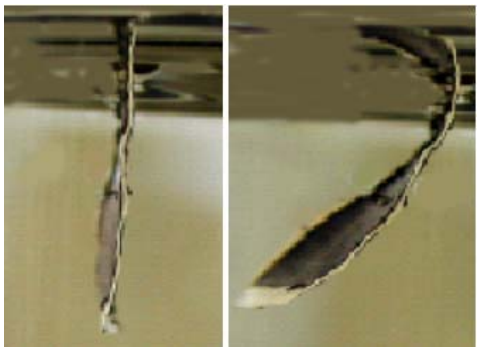

Figure 4. Conductive EAP actuator (left) activated by 2Vand 30 mA is shown bending (right)
(Courtesy of JPL/Caltech).

2.2.4 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 changes that affect the ionic charge balance between the NT and the electrolyte. The more changes are injected into the bond the larger the dimension changes. 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 lengthening of the bond resulting in an increase in nanotube 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 stress. Further, since carbon offers high thermal stability, carbon nanotubes may eventually be used at temperatures greater than 1000ºC, which far exceeds the capabilities of alternative high-performance actuator materials. 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. A carbon nanotube actuator can be constructed by laminating two narrow strips that are cut from a carbon nanotube sheet using an intermediate adhesive layer, which is electronically insulated. The resulting “cantilever device” is immersed in an electrolyte such as a sodium chloride solution, and an electrical connection is made in the form of two nanotube strips. Application of about 1,0 V is sufficient to cause bending, and the direction depends on the polarity of the field.

2.2.5 ElectroRheological Fluids (ERF)

ElectroRheological fluids (ERFs) “Fig. 5” 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 electrorheological 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 phenomenal and the theoretical basis for their behavior can be found in (Bar-Cohen, 2001g).

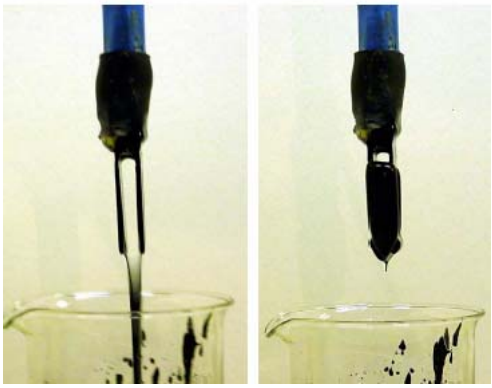

Figure 5. Electrorheological fluid at reference (left) and activated states (right).
(Courtesy of Smart Technology Limited, UK)

3. Applications that are being explored

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

3.1 Medical applications

The growing availability of EAP materials that exhibit high actuation displacements and forces is opening new avenues to bioengineering in terms of medical devices and assistance to humans in overcoming different forms of disability. Areas that are being considered include hearing ids, vocal cords, and rehabilitation robotics. For the latter, exoskeleton structures are being considered in support of rehabilitation or to augment the mobility and functionalities of

patients with weak muscles. To support such efforts, research is currently underway to establish a test bed and models. Some of the medical applications that are currently being considered include: EAP for Biological Muscle Augmentation or Replacement; Miniature in-Vivo EAP Robots for Diagnostics and Microsurgery (minimally invasive surgery) “Fig. 6”; Catheter Steering Mechanism; Tissues Engineering; Interfacing Neuron to Electronic Devices using EAP and Active Bandage.

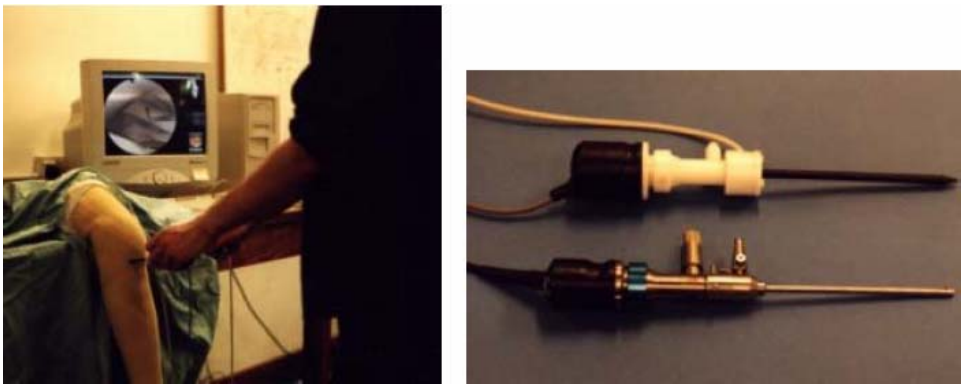

Figure 6. Knee Arthroscopy Training System and Mock Arthroscope (top) compared to a real instrument (bottom) [Courtesy of Simulation and Visualization Research Group website].

3.2 Human-Machine Interfaces

Interfacing between human and machine to complement or substitute our senses can enable important capabilities for possible medical applications or general use. In the last five years a number of such interfaces, which employ EAP, were investigated or considered. Of notable significance is the ability to interface machines and the human brain. Such a capability addresses a critical element in the operation of prosthetics that may be developed using EAP actuators. A recent development by scientists at Duke University (Wessberg et al, 2000) enables this possibility where electrodes have been connected to the brain of a monkey and using brain waves of the monkey to operate a robotic arm, both locally and remotely via the internet. Using such a capability to control prosthetics would require feedback to allow the human operator to “feel” the environment around the artificial limbs. Such feedback can be provided with the aid of tactile sensors, haptic devices, and other interfaces, “Fig. 7”.

Figure 7. Tactile Interface for Teleoperation, Tactile Interface Operating in a vibration mode and The Teletact. (Courtesy of University of Salford)

3.3 Haptic/Tactile Interfaces

To address the need for interacting with remote and virtual worlds, the engineering community has started developing haptic (tactile and force) feedback systems (Burdea, 1996). At the present time, haptic feedback is a less-developed modality for interacting with remote and virtual worlds compared with visual and auditory feedback. Thus, realism especially suffers when remote and virtual tasks involve dexterous manipulation or interaction in visually occluded scenes.

Tactile sensing is created by skin excitation that is usually produced by devices known as “tactile displays”. These skin excitations generate the sensation of contact. Force-sensitive resistors, miniature pressure transducers, ultrasonic force sensors, piezoelectric sensors, vibrotactile arrays, thermal displays, and electrorheological devices are some of the innovate technologies that have been used to generate the sensation touch. While tactile feedback can be conveyed by the mechanical smoothness and slippage of a remote object, it cannot convey the mechanical compliance, weight, or inertia of the virtual object being manipulated.

Force-feedback devices are designed to apply forces or moments at specific points on the body of a human operator. The applied force or moment is equal or proportional to a force or moment generated in a remote or virtual environment. Thus, the human operator physically interacts with a computer system that emulates a virtual or remote environment. Force-feedback devices include portable and nonportable interfaces. Force-feedback joysticks, mice and small robotic arms such as the Phantom are nonportable devices that allow users to feel the geometry, hardness, and/or weight of virtual objects. Portable systems are force-feedback devices that are grounded to the human body. They are distinguished as arm-exoskeleton if they apply forces at the human arm and as hand masters if they apply forces at a human's wrist and/or palm.

Portable hand masters are haptic interfaces that apply forces to the human hand while they are attached at the human operator forearm. In most cases, these systems look like gloves where the actuators placed at the human forearm, and forces are transmitted to the fingers using cables, tendons and pulleys.

The development of a haptic interfacing mechanism that will enable a remote operator to "feel" the stiffness and forces at remote or virtual sites. These interfaces are based on novel mechanisms conceived by JPL and Rutgers University investigators in ca system called MEMICA, "Fig. 8".

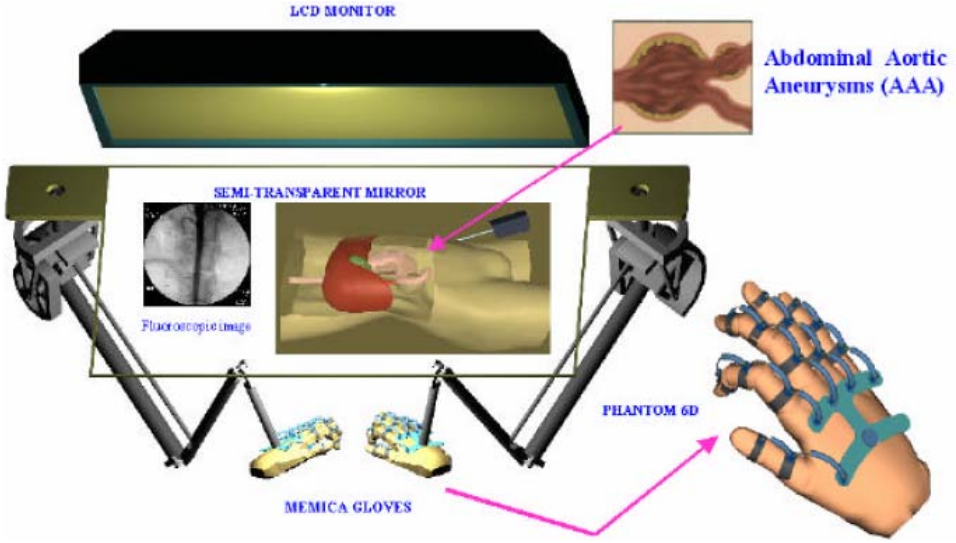

Figure 8. Performing virtual reality medical tasks via the electrorheological fluid based MEMICA haptic interface. (Courtesy of JPL/NASA)

4. 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.

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