ROBOTIC ARM ACTUATED BY ELECTROACTIVE POLYMERS

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Abstract. *Actuators are used for many planetary and space applications. To meet the NASA goal to reduce the actuators size, mass, cost and power consumption, electroactive polymers (EAP) are being developed to induce large bending and longitudinal actuation strains. Comparison between EAP and the widely used transducing actuators shows that, while lagging in force delivering capability, these materials are superior in mass, power consumption and actuation strain levels. This reported study is concentrating on the development of effective EAPs and the resultant enabling mechanisms that employ their unique characteristics. Several EAP driven mechanisms, which emulate human hand, were developed including a gripper, manipulator arm and surface wiper. The manipulator arm was made of a composite rod that was lifted by a longitudinal scrolled rope actuator and had an end-effector gripper with bending EAP fingers allowing to grab and hold such objects as rocks. A EAP surface wiper was developed to operates like a human finger and to remove dust from windows and solar cells. These EAP driven devices take advantage of the large displacement capability of these materials where there is a limited requirement for a force actuation capability.*

Key Words. Robotics, Electroactive Polymers, Hand Simulation, Actuators

1 INTRODUCTION

Efficient miniature actuators that arc light, compact and driven by low power are needed to drive telerobotic devices and space mechanisms in future NASA missions. Examples of space mechanisms and devices that require actuators include robotic arm., rovers, release mechanisms, antenna and instrument deployment, positioning devices, aperture opening and closing devices, and real-time compensation for thermal expansion in space structures, etc. Electroceramics (piezoelectric and electrostrictive) offer effective, compact, actuation materials and they are incorporated into such mechanisms as ultrasonic motors, inchworms, translators and manipulators.

" In contrast to electroceramics, electroactive polymers (EAP) are emerging as new actuation materials [1] with displacement capabilities that cannot be matched by the strict ion-l imited and rigid ceramics. Table 1 shows a comparison between the capability of EAP materials, electroactive ceramics (EAC) and shape memory alloys (SMA). As shown in Table 1, EAPs are lighter and their strict ion capability can be as high as two orders of magnitude more than EACs. Further, their response speed is significantly higher than SMAS. The authors' current study is directed towards taking advantage of these polymers' resilience and the ability to engineer their properties. The mass producibility of polymers and the fact that EAT's do not require poling (in contrast to piezoelectric materials) help to produce them at low cost. EAPs can be easily formed in various shapes and can be used to build micro-electro-mechanical systems (M EMS). They can be designed to emulate the operation of biological muscles [2-4] with unique characteristics of high toughness, large actuation strain constant and inherent vibration damping.

TABLE 1: comparison of the properties of EAP, SMA and EAC

Propert y	Electroactive polymers (EAP)	Elect react ive Ceramics (EAC)	Shape memory alloys (SMA)
Actuation strain	>10%	0.1 -0.3 %	<8%*
Force (MPa)	0.1-3	30-40	about 700
Reaction speed	μsec to SCC	μsec to Scc	scc to min
Density	1- 2.5 g/cc	6-8 glee	**5-6** g/cc
Drive voltage	2-7 V/l 0-1 00V/μm	50-800 v	NA
Consumed Power	m-watts	watts	Watts
Fracture toughness	resilient, elastic	fragile	Elastic

Note: The fatigue life at this level of strain is very life

The development of muscle actuators is involved with an interdisciplinary effort using expertise in materials science, chemistry, electronics, and robotics. At the initial phase of the authors' study efforts were made to identify electroactive polymers that induce large actuation strains. Two categories of EAPs were identified including (a) bending act uators: Ionic-Polymer/Plat inum composites (1 PPC); and (b) longitudinal act uators: electrostatically activated EAPs. These two EAP actuators offer the capability to bend or stretch/extend, which essentially emulate the operation of biological muscles and limbs. In the second phase, efforts were made to identify robotic and planetary applications and demonstrate the EAP actuators capability. In the current phase the efforts arc concentrated on determining EAPs capability to operate at space conditions of low temperat ures and vacuum. Also, studies arc taking place to determine the capability to control and obtain feedback using EAP actuators.

2 IONOMERS AS BENDING EAP ACTUATORS

The bending EAP actuator is composed of a perfluorinated ionic pol ymer/platinum composite material, where platinum electrodes are deposited on both sides. After O.18-mm thickness 1 PPC

" **films** are formed they are cut to strips that are **25x3.5-mm** in **size** and weighing 0.1 -g. To maintain the actuation capability of IPPC, the material needs to be kept moist continuously. Efforts are currently being made to overcome this limitation and success was observed when using thick platinum electrodes and limiting the voltage to <2-V rather than the levels of 3-5 volts. Using such electrodes, an 1 PPC film was demonstrated to operate continuously for more than one million cycles. In addition to the use of thick platinum, efforts arc made to form a coating seal using encapsulation methods as a quasi-skin to protect the ionic constituents of the IPPC films.

The structure and properties of the IPPC have been the subject of numerous investigations (see for example [5]). One of the interesting properties of this material is its ability to absorb large amounts of polar solvents, i.e. water. In order to chemically electrode 1 PPCs, platinum (Pt) metal ions are dispersed throughout the hydrophilic regions of the polymer, and are subsequently reduced to the corresponding zero valent metal atoms. This results-in the formation of a dendritic type electrode. When equilibrated with aqueous solutions these membranes arc swollen and they contain a certain amount of water. Swelling equilibrium results from the balance between the elastic forces of the polymeric matrix and the water affinity to the fixed ion-exchanging sites and the moving counter ions. The water content depends on the hydrophilic properties of the ionic species inside the membrane and also on the electrolyte concentration of the external solution. To enhance the force actuation capability of 1 PPCs, techniques of producing thicker films as well as modification of the ionomer processing were investigated. Success was observed in processing the material to induce more than two times the strain with a higher response consistency. To better understand the actuation mechanism in ionomers the phenomena is studied and modeled. Also, alternative ionomer actuators arc being searched.

When an external voltage is applied on an 1 PPC film, it bends towards the anode at a level that increases with the voltage (see Figure 1). Exposure to lower temperature.s reduced the response amplitude of the ionomer as shown in Figure 2. In an experiment that lasted over 6 hours it was shown that while the response dropped by more than 75°/0 at -140['~ the decrease was a reversible process. The ionomer response returned to its orginal level at room temperature. Under AC voltage, the film undergoes swinging movement and the displacement level depends not only on the voltage magnitude but also on the frequency. Lower frequencies (down to 0.1 or 0.01 Hz) lead to higher displacement, which has a saturation level that depends on the frequency. The movement of the muscle is controlled by the applied electrical source but it is strongly affected by the water content that serves as an ion transport medium. The operation of the ionomer as a bending actuator is demonstrated in a configuration of a window surface wiper in Figure 3, where the ionomer was driven by 2.5V, which removed the dust. As can be seen in this Figure, an ionomer strip is attached to the surface of a glass plate and was actuated left or right as desired by changing the polarity of the drive voltage.

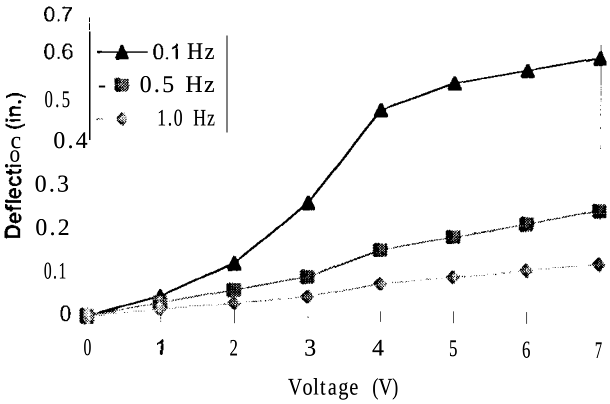

Figure 1: The response of ionomer to various voltage amplitude levels at three different frequencies.

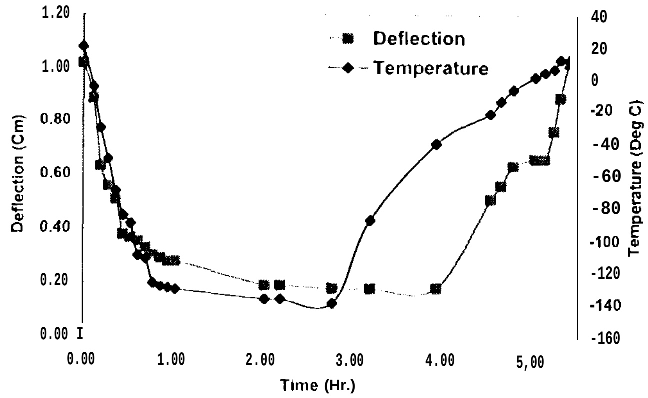

Figure 2: Deflection amplitude of the ionomer as a function of time and temperature.

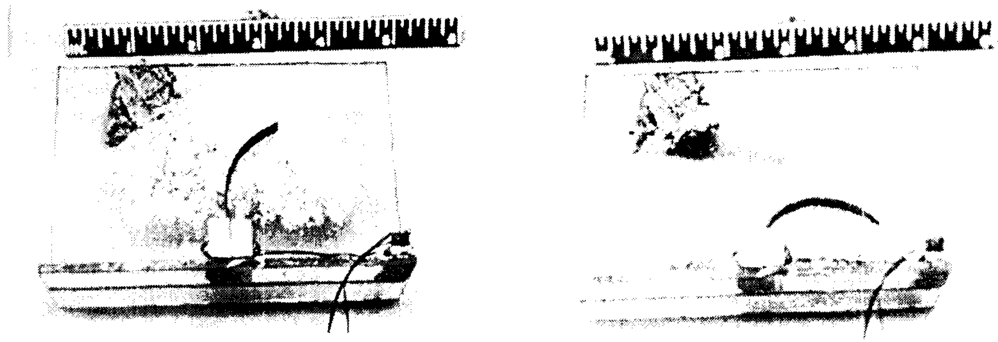

Figure 3: A view of a surface wiper with a simulated window and dust, where an ionomer is bending back and forth next to a glass plate.

Recent tests of the performance of the ionomers at low temperatures showed that while the response decrease with temperature, a sizeable displacement was still observed at -1 50°C. This decrease can be compensated by increase in voltage and it is interesting to point out that the response saturation occures at much higher voltage levels at low temperatures. Another interesting observation is the increase in the power consumption level that occurs at low temperatures. Tests were conducted both at room temperature and at - 100°C and the results are shown above in Figures 4 and 5.

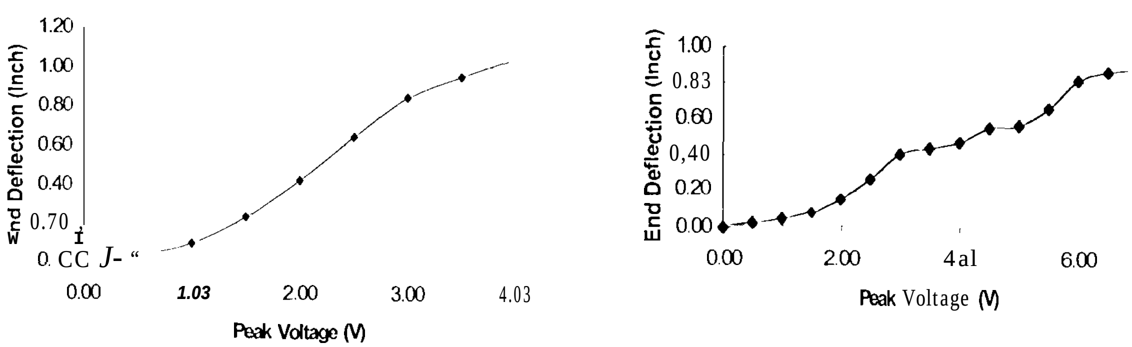

Figure 4: Response of bending ionomer 0.1 Hz electro-activation at (right) Room temperature and (left) -1 00(' C.

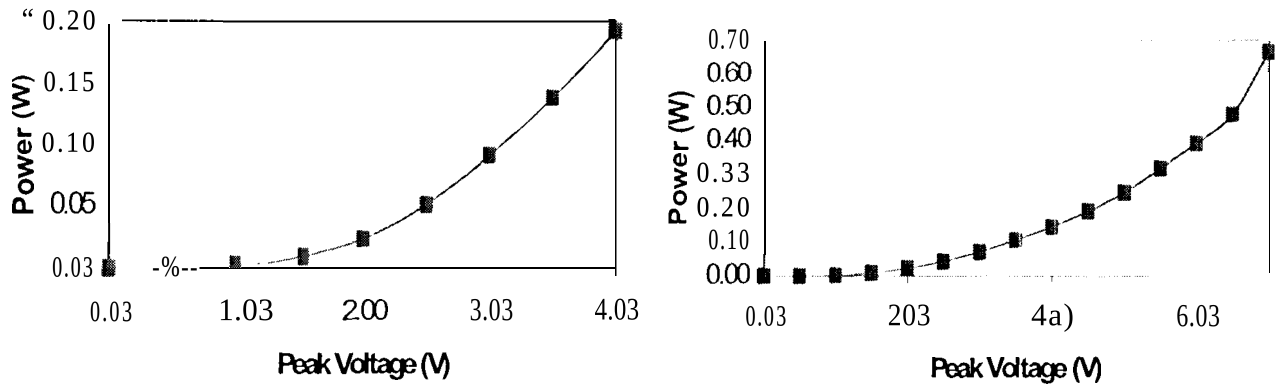

Figure 5: Power consumption of bending ionomer subjected to 0.1 Hz electro-activation at (right) room temperature and (left) - 100° C.

3 LONGITUDINAL ELECTROSTATIC POLYMER ACTUATORS

Polymers with low elastic stiffness and high dielectric constant can be used to induce large actuation strain by subjecting the material to an electrostatic field. These characteristics of polymers allow producing longitudinal actuators that operate similar to biological muscles. The governing principle is the response of the material to Coulomb forces between charged particles. Traditional electrostatic actuators arc fabricated as a capacitor with parallel electrodes with a thin air gap between them. One of the major disadvantages of this type of actuators is their relatively low breakdown voltage. The authors adopted the approach that was reported in reference [4], where a longitudinal electrostatic actuator was made of dielectric elastomer film coated with carbon electrodes. The force (stress) that is exerted normally on such a film with compliant electrodes is as follows:

$$P = \varepsilon\varepsilon_0 E^2 = \varepsilon\varepsilon_0 (V/t)^2$$

Where: P is the normal stress, ε_0 is the permittivity of vacuum and ε is the relative permittivity (dielectric constant) of the material, E is the electric field across the thickness of the film, V is the voltage applied across the film and t is the thickness of the film.

Examining the equation above, it is easy to notice that the force magnitude is twice as large as that for the case of rigid parallel electrodes. To obtain the thickness strain the force needs to be divided by the elastic modulus of the film. Use of polymers with high dielectric constants and application of high electric fields allow inducing large forces and strains. To obtain the required electric field levels there is a need for either to use high voltage and/or employ thin films. For elastomers with low elastic modulus, it is reasonable to assume a Poisson>s ratio of 0.5. This means that the volume of the polymer is kept constant while the film is deformed under the applied field. As a result, the film is squeezed in the thickness direction causing expansion in the transverse plane. For a pair of electrodes with circular shape, the diameter and thickness changes can be determined using the following relation, where the second order components arc neglected.

$$\Delta D / D_0 = (1/2)\Delta t / t_0$$

Where: D_0 is the original diameter of the electrodes and ΔD is the resultant diameter change, t_0 is the original thickness and the Δt is its change under electric activation.

To produce a longitudinal actuator with large actuation force, a stack of two silicone layers (Dow Corning Sylgard 186) was used with carbon electrodes on both sides of one of the layers. The two layers were rolled to form a rope as the one shown photographically next to a scale in Figure 6. The displacement in the rope cross section is a rotational one around the rope axis and it is constrained by interlaminar stresses. Therefore, the total actuation extension of the rope is proportional to its length and the resultant actuation force is proportional to the cross-section area normal to the axis. To develop an EAP muscle using such a rope, the length and diameter are used as design parameters, enabling the adaptation of the rope actuator to specific applications.

4 ROBOTIC APPLICATIONS USING EAP ACTUATOR

The availability of EAP actuators that can bend or extend/contract allows producing unique robotic devices that emulate human hands. The authors investigated several potential applications including gripper, robotic arm and surface wiper. As shown earlier, IPPC composite films are demonstrating a remarkable bending strain under a relatively low voltage drive, using a very low power. However, these ionomers are demonstrating a relatively low force actuation capability. Since IPPCs are made of a relatively strong material with a large strain capability, they were employed similar to the function of human fingers. In Figure 7, a gripper is shown using IPPC fingers in the form of an end-effector of miniature low mass robotic arms. The fingers move back and forth to allow opening similar to human hand, embracing the desired object and gripping on it. The hooks at the end of the fingers are function similar to fingernails to secure the gripped object.

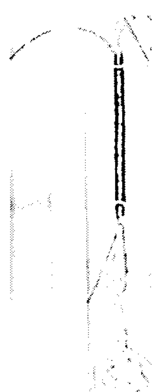

Figure 6: Electrostatic rope with a rock mounted on its bottom.

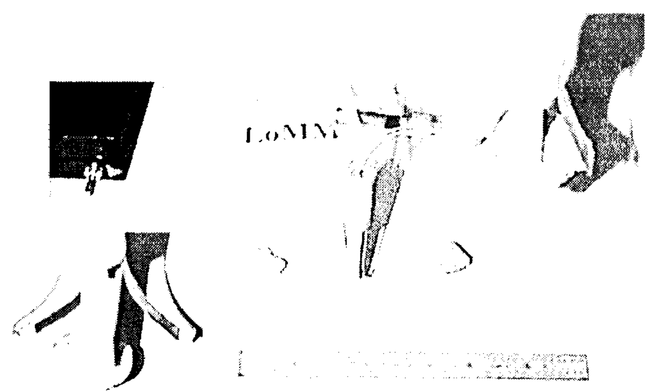

Figure 7: A 4-finger IPPC end-effector gripper lifting 10.3-g rock.

So far, multi-finger grippers that consist of 2- and 4-fingers were produced, where the 4-finger gripper lifted a mass of 10.3-g. This gripper prototype was mounted on a 5-mm diameter graphite/epoxy rod to form lightweight am. The gripper was driven by 2 to 5-V square wave signal at a frequency of 0.1 -Hz to allow sufficient time to perform a demonstration of the gripper capability. To operate the gripper its fingers are opened and the gripper is brought near the object to be collected. At this point the fingers are closed and the object is lifted. The demonstration of the gripper capability to lift a rock was intended to pave the way for a future application to planetary sample collection tasks providing miniature ultra-dexterous and versatile tool. To allow lifting the robotic arm, a set of two ropes was used as shown in Figure 8. One rope actuates the arm by tilting its balance and its lifting displacement is determined by the ratio between its connection distance from the pivot point compared to the gripper distance. The other rope is a longer one and is connected directly to the gripper that is lifted or dropped as a function of the rope actuation displacement. Figure 8 shows the full robotic arm with the two longitudinal rope actuators and the gripper with ionomer fingers gripper.

Lesson learned from Viking and Mars Pathfinder missions indicates that the operation on Mars is involved with an environment that causes the accumulation of dust on the hardware surfaces. The dust accumulation is a critical problem that hampers long-term operation of optical instruments and degrades the produced power efficiency of solar cells. To remove dust from surfaces one can use a similar mechanism as the windshield wipers of cars. Unfortunately, conventional surface wiping mechanisms are cumbersome, heavy, power gazzler and cannot be practical for such tasks as cleaning individual solar cells. On the other hand, 1 PPC bending actuator has the ideal characteristics of surface wiper. As shown in Figure 3, a simple, small, lightweight, low power consuming surface wiper can be constructed using an ionomer film. The ionomer responds to activation signals at the millisecond range and the angle of bending can exceed 180 degrees span and can cover 25-40 mm diameter of a circular area using about 40-50 mm long wiper. The wiper element can be set straight in the middle of the desired area and activated to sweep left and right by switching the electric field polarity. Also, it can be set on the side of the desired area and activated in one direction.

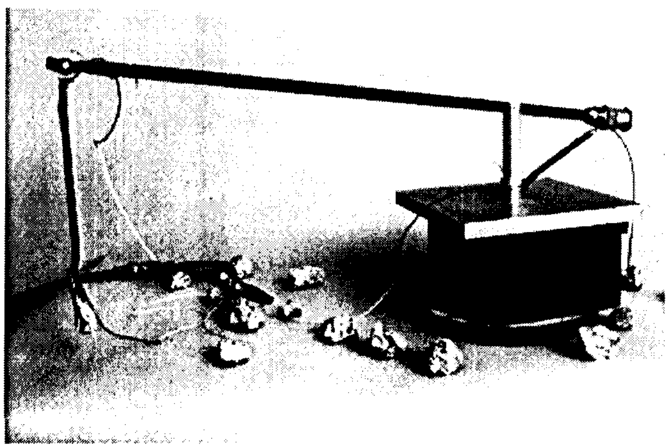

FIGURE 8: A view of the robotic arm that is driven by EAP actuators.

5 CONCLUSION

Two types of electroactive polymer actuators, which induce large displacement actuation, were employed in this study to develop robotic devices that emulated human hands. While the material performance is being enhanced, methods of controlling the actuation performance are being investigated. 1 PPCs are offering a large bending actuation and allow emulating the dexterity of human hand using lightweight material that consumes low power and is inexpensive to produce. For longitudinal displacement actuation, electrostatically activated films were rolled to form ropes and to serve equivalently to biological muscles. These electroactive polymers are showing a superior actuation displacement, mass, cost, power consumption and fatigue characteristics over conventional electromagnetic, EACs and SMAS. While the force actuation capability of EAPs is limited, their actuation displacement levels arc unmatched. Telerobotic devices were constructed using EAP and allowed actuation of unique mechanisms. A multi-finger gripper was demonstrated to have large finger opening and closing with great mass carrying capability. A robotic arm was constructed similar to human hand using a composite rod, electrostaticall y driven rope and a 4-finger IPPC gripper as end-effecters. Currently, the practical application of IPPCs is constrained by the need to maintain the ionic constituents and preventing the film from drying. The equivalent of a biological skin is being investigated to protect the ion content of IPPC films. Encapsulation techniques arc being investigated to assure the moisture containment and so far success was observed when using thicker platinum electrodes and voltage levels below 2-volts. To address the issue of dust on Mars, a unique surface wiper that is equivalent to a moving human finger was developed to allow removal of dust from windows anti solar cells using low power, light-weight ionomer films.

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