Proceedings of SPIE's 5th Annual International Symposium on Smart Structures and Materials, 1-5 March, 1998, San Diego, CA. Paper No. 3329-07

Flexible, low-mass robotic arm actuated by electroactive polymers

Y. Bar-Cohen[a], T. Xue[a], M. Shahinpoor[b], J. O. Simpson[c], and J. Smith[c]
[a]Jet Propulsion Laboratory (JPL), Caltech., Pasadena, CA, yosi@jpl.nasa.gov
[b]Artificial Muscles Research Institute, University of New Mexico, Albuquerque, NM
[c]Composites and Polymers Branch, NASA LaRC, Hampton, VA

ABSTRACT

Miniature, lightweight, low-cost actuators that consume low-power can be used to develop unmatched robotic devices to make an impact on many technology areas. Electroactive polymers (EAP) actuators offer the potential to produce such devices and they induce relatively large bending and longitudinal actuation strains. This reported study is concentrating on the development of effective EAPs and the resultant enabling mechanisms employing 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 with a lifting actuator consisting of a scrolled rope that is activated longitudinally by an electrostatic field. A gripper was made to serve as an end effector and it consisted of multiple bending EAP fingers for grabbing and holding such objects as rocks. An EAP surface wiper was developed to operate like a human finger and to demonstrate the potential to remove dust from optical and IR windows as well as solar cells. These EAP driven devices are taking advantage of the large actuation displacement of these materials for applications that have limited requirement for actuation force capability.

Keywords: Miniature Robotics, Electroactive Polymers, Hand Simulation, EAP Actuators, Surface Wiper, EAP Gripper

1. INTRODUCTION

Efficient miniature actuators that are 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 arms, miniature rovers, release mechanisms, 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 [Furukawa and Wen, 1984] with displacement capabilities that cannot be matched by the striction-limited and rigid ceramics. EAPs are lighter and their striction capability can be as high as two orders of magnitude more than EACs [Bar-Cohen, Xue, et al, 1997]. Further, their response speed is significantly higher than Shape Memory Alloys (SMAs). The authors' current study is directed towards taking advantage of these polymers' resilience and the ability to engineer their properties. The mass producability of polymers and the fact that EAPs 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 (MEMS). They can be designed to emulate the operation of biological muscles [Hunter and Lafontaine, 1992; Kornblush, et al, 1995; and Shahinpoor, 1994] with unique characteristics of high toughness, large actuation strain constant and inherent vibration damping.

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 actuators: Ion exchange membrane platinum composites; and (b) longitudinal actuators: 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 actuator capability. Current efforts are concentrated on determining EAPs capability to operate at space conditions of low temperatures and vacuum. Also, studies are 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 perfluorinated ion exchange membrane platinum composite (IMPC), where platinum electrodes are deposited on both sides. After 0.18-mm thickness IMPC films are formed they are cut to strips that are 25.0x3.5-mm in size and weighing 0.1-g. To maintain the actuation capability of IMPC, the material needs to be kept moist continuously and providing the necessary ions that are responsible for the actuation. Efforts are currently being made to protect the moisture content and some 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 IMPC film was demonstrated to operate continuously for more than several hours. In addition to the use of thick platinum, efforts are made to form a coating seal using encapsulation methods as a quasi-skin to protect the moisture inside the IMPC films.

The structure and properties of the IMPC have been the subject of numerous investigations (see for example [Heitner-Wirguin, 1996]). 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 IMPCs, 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 are 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 IMPCs, techniques of producing thicker films as well as modification of the ionomer processing were investigated. Using twice thicker Nafion (#120 Dupont product) to produce bending ionomer actuators led to force actuation that is more than 20% higher than the original Nafion (#117). To better understand the actuation mechanism in ionomers the phenomena is studied and modeled. Also, alternative ionomer actuators are being searched.

When an external voltage is applied on an IMPC film, it causes bending towards the anode at a level that increases with the voltage, which reaches saturation as shown in Figure 1. Under AC voltage, the film undergoes swinging movement and the displacement level depends not only on the voltage magnitude but also on the frequency. Generally, activation at lower frequencies (down to 0.1 or 0.01 Hz) induces higher displacement. The level at which the bending reaches saturation as function of the drive voltage dependents on the frequency and it is lower at higher frequencies. 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 2, where the ionomer was driven by 2.5V to remove sawdust. 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. 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 -140^{o}C. This decrease can be compensated by increase in voltage and it is interesting to point out that, at low temperatures, the response reaches saturation at much higher voltage levels.

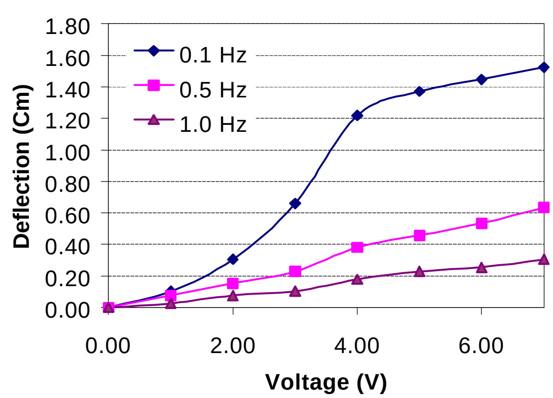


Figure 1: The response of ionomer to various voltage amplitudes at three different frequencies.

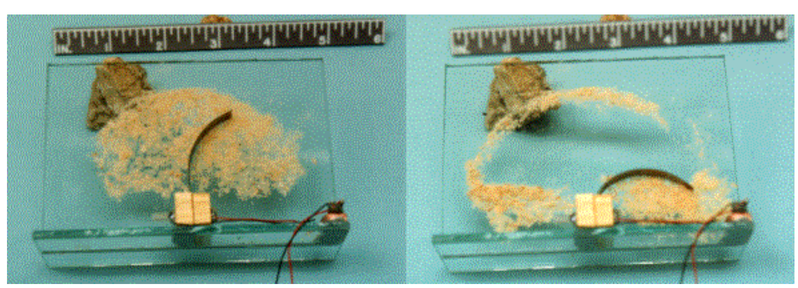


Figure 2: A view of a surface wiper with a simulated window and dust, where an ionomer is bending back and forth next to a glass plate.

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 using Coulomb forces between electrodes to squeeze or stretch the material. Traditional electrostatic actuators are 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 by Kornslush, et al, 1995, 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:

$$P = \varepsilon\varepsilon_0 E^2 = \varepsilon\varepsilon_0 (V / t)^2 \qquad (1)$$

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 induces large forces and strains. To obtain the required electric field levels one needs to either 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 are neglected.

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

Where: D_0 is the original diameter of the electrodes and ΔD is the resultant diameter change, t_0 is the original thickness and 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 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. The components of a robotic arm, which are shown schematically in Figure 3, were produced in this current study.

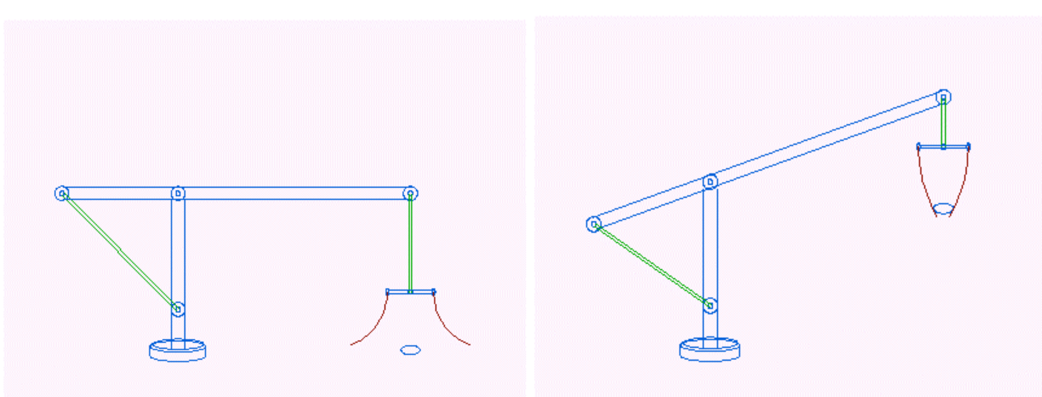


Figure 3: A simulated view of a configuration of a robotic arm, which takes advantage of the capability of longitudinal and bending EAP actuators.

As shown earlier, under a relatively low activation power and drive voltage, IMPC actuators are induced with remarkable level of bending strain. However, these ionomers are providing a relatively low force actuation capability. Since IMPCs are made of a relatively strong material, the large strain can be employed to produce a gripper that functions similar to human fingers. The fingers move back and forth opening and closing the gripper similar to human hand, embracing the desired object and gripping on it. The hooks at the end of the fingers are functioning similar to fingernails to hold the object securely. So far, multi-fingered grippers that consist of 2- and 4-fingers were produced, where the 4-finger gripper lifted a mass of 10.3-g (shown in Figure 4). 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 lift a robotic arm and its end-effector a scrolled rope longitudinal EAP actuator was used as shown in Figure 5. A rock was mounted at the end of the scrolled rope and was dropped as a result of applying electric field onto the film that makes the rope. The overall voltage is at the level of 30-70 V/μm, which reached between 2000 and 2500-Volts for the rope shown in Figure 5. Since the film is squeezed as a result of the activation, it becomes longer under the electro activation making the rope longer.

To form a miniature lightweight arm a 5-mm diameter graphite/epoxy rod was used and a set of two ropes to lower and raise the arm as shown in Figure 6. 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 end-effector or object that is lifted or dropped as a function of the rope actuation displacement. Figure 6 shows the robotic arm with the two longitudinal rope actuators.

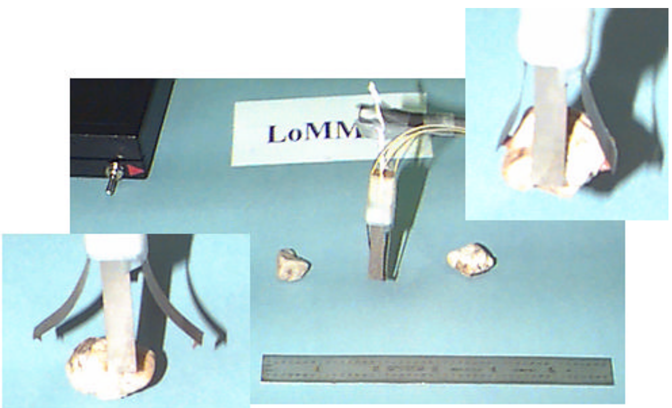


Figure 4: A 4-finger IMPC end-effector gripper lifting 10.3-g rock.

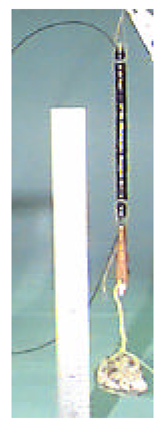
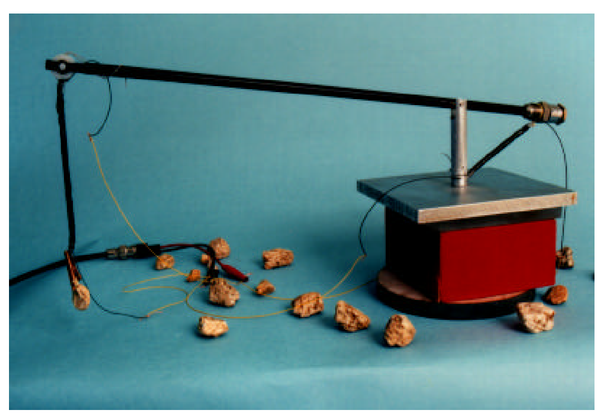


Figure 5: Electrostatic rope with a rock mounted on its bottom.

Figure 6: A view of a miniature graphite/epoxy arm that is activated by EAP scrolled rope.



Lessons learned from Viking and Mars Pathfinder missions indicate 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 guzzler and cannot be practical for such tasks as dusk removal from individual solar cells. Contrary to conventional actuators, IMPC bending actuator has the ideal characteristics that are necessary to produce surface wipers. As shown in Figure 2, a simple, miniature, 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 while covering 25-40 mm diameter of a semi-circular area using about 40-50 mm long wiper. The wiper element can be placed 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 located on the side of the desired area and activated in one direction.

5. CONCLUSION

Two types of electroactive polymer actuators, which induce large displacement actuation, were employed in this study to develop components of a robotic arm that emulated human hands. While the material performance is being enhanced, methods of controlling the actuation performance are being investigated. IMPCs are offering a large bending actuation and allow emulating the dexterity of human hand and fingers using lightweight low power consuming material that 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, EAC and SMA actuators. While the force actuation capability of EAPs is limited, their actuation displacement levels are unmatched. Telerobotic devices were constructed using EAPs enabling the actuation of unique mechanisms. A multi-finger gripper was demonstrated to have large finger opening and closing with a large mass carrying capability. The components of a miniature robotic arm were constructed similar to human hand using a composite rod and a scrolled rope electrostatic actuator for the lifting mechanism and a 4-finger IMPC gripper as an end-effector. Currently, the practical application of IMPCs is constrained by the need to prevent the film from drying and thus maintaining its ionic constituents. The equivalent of a biological skin is being investigated to protect the IMPC film from drying and encapsulation techniques are being investigated to protect the moisture content of the IMPC films. So far limited 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 and it feasibility was demonstrated by removing sawdust from a glass plate. Such a wiper has the potential to serve as a means of removing dust from windows and solar cells using low power, light-weight ionomer films.

6. ACKNOWLEDGEMENT

The results reported in this manuscript were obtained under a TRIWG task, Code S. Mr. David Lavery and Dr. Chuck Weisbin are the Managers of TRIWG. The authors would like also to express their appreciation of Brian Lucky, Cinkiat Abidin, Marlene Turner and Harry Mashhoudy, who are students at the Integrated Manufacturing Engineering Dept. of UCLA. These students contributed greatly to the fabrication of the robotic arm and the electrostatic rope muscle.

7. REFERENCES

Bar-Cohen, Y., T. Xue, B. Joffe, S.-S. Lih, P. Willis, J. Simpson, J. Smith, M. Shahinpoor, and P. Willis, "Electroactive Polymers (EAP) Low Mass Muscle Actuators," *Proceedings of SPIE, Vol. SPIE 3041, Smart Structures and Materials 1997 Symposium, Enabling Technologies: Smart Structures and Integrated Systems*, Marc E. Regelbrugge (Ed.), ISBN 0-8194-2454-4, SPIE, Bellingham, WA (June 1997), pp. 697-701.

Furukawa and J. X. Wen, "Electrostriction and Piezoelectricity in Ferroelectric Polymers," Japanese Journal of Applied Physics, Vol. 23, No. 9, pp. 677-679, 1984.

Heitner-Wirguin, C. "Recent advances in perfluorinated ionomer membranes: Structure, properties and applications," *Journal of Membrane Science*, V 120, No. 1, pp. 1-33, 1996.

Hunter I. W. and Lafontaine, S. "A comparison of muscle with artificial actuators," *IEEE Solid-State Sensor and Actuator Workshop*, pp. 178-165, 1992.

Kornbluh, R. Pelrine R. and Joseph, J. " Elastomeric dielectric artificial muscle actuators for small robots," *Proceeding of the 3rd IASTED International Conference*, Concun, Mexico, June, 14-16, 1995.

Shahinpoor, M., "Continuum electromechanics of ionic polymeric gels as artificial muscles for robotic applications," *Smart Materials and Structures*, Vol. 3, pp. 367-372, 1994.