CHALLENGES TO THE TRANSITION OF IPMC ARTIFICIAL MUSCLE ACTUATORS TO PRACTICAL APPLICATION

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ABSTRACT

In recent years, electroactive polymers (EAP) materials have gained recognition as potential actuators with unique capabilities having the closest performance resemblance to biological muscles. Ion-exchange membrane metallic composites (IPMC) are one of the EAP materials that were shown to have potential application as actuators. The strong bending that is induced by IPMC offers attractive actuation for the construction of various mechanisms. Examples of applications that were conceived and investigated for planetary tasks include a gripper and dust wiper. The development of the wiper for dust removal from the window of a miniature rover planned for launch to an asteroid is the subject of this reported study. The application of EAP in space conditions is posing great challenge due to the harsh operating conditions that are involved and the critical need for robustness and durability. The various issues that can affect the application of IPMC were examined including operation in vacuum, low temperatures, and the effect of the electromechanical and ionic characteristics of IPMC on its actuation capability. The authors introduced highly efficient IPMC materials, mechanical modeling, unique elements and protective coatings in an effort to enhance the applicability of IPMC as an actuator of a planetary dust-wiper. Results showed that the IPMC technology is not ready yet for practical implementation due to residual deformation that is introduced under DC activation and the difficulty to protect the material ionic content over the needed 3-years durability. Further studies are under way to overcome these obstacles and other EAP materials are also being considered as alternative bending actuators.

INTRODUCTION

Consideration of practical applications for electroactive polymers (EAP) has began only in this decade as a result of the emergence of new materials that induce large displacements [Hunter and Lafontaine, 1992; Kornbluh, et al, 1995; and Bar-Cohen, 1999b]. These materials are highly attractive for their low-density and large strain capability, which can be as high as two orders of magnitude greater than the striction-limited, rigid and fragile electroactive ceramics (EAC) [Bar-Cohen, et al, 1997; and Osada & Gong, 1993]. Also, these materials are superior to shape memory alloys (SMA) in their spectral response, lower density, and resilience. However, EAP materials reach their elastic limit at low stress levels, with actuation stress that falls far shorter than EAC and SMA actuators. The most attractive feature of EAP materials is their ability to emulate biological muscles with high toughness, large actuation strain and inherent vibration damping. EAP actuation similarity to biological muscles gained them the name "Artificial Muscles" and offers the potential of developing biologically inspired robots. Such biomimetic robots can be made highly maneuverable, noiseless and agile, with various shapes including insect-like. Effective EAP offers the potential of making science fiction ideas a faster reality than feasible with any other conventional actuation mechanism. Unfortunately, the force actuation and mechanical energy density of EAP materials are relatively low, are limiting at the present time the potential applications that can be considered for practical use. Further, there are no commercially available effective and robust EAP materials and there is no reliable database that documents the properties of the existing EAP materials. To overcome these limitations there is a need for development in numerous multidisciplinary areas from computational chemistry, comprehensive material science, electromechanical analysis, and actuation characterization as well as improved material processing techniques. Efforts are needed to gain a better understanding of the parameters that control the electromechanical interaction. The processes of synthesizing, fabricating, electroding, shaping and handling will need to be refined to maximize their actuation capability and robustness.

Since EAP can be used to make actuators that are light, compact and driven by low power, the authors sought to take advantage of their resilience and fracture toughness to develop space applications. The harsh environment associated with space environment poses great challenges to the application of EAP. Addressing these challenges have been the subject of the NASA task called Low Mass Muscle Actuators (LoMMAs), under the lead of the principal author and several EAP materials and applications were investigated. The emphasis of this paper is on Ion-exchange membrane metallic composites (IPMC), which are bending EAP materials. IPMC were first reported in 1992 [Oguro et al, 1992; Sadeghipour, et al, 1992 and Shahinpoor, 1992]. The various issues that can be affect the application of IPMC were examined including operation in vacuum, low temperatures, and the effect of the electromechanical and ionic characteristics of IPMC on its actuation capability. The finding that IPMC can be activated at low temperatures and vacuum, paved the way for the serious consideration of this class of materials for space applications [Bar-Cohen, et al, 1997]. Its bending characteristics offered the potential to address the critical issue of planetary dust that affects solar cells and imaging instruments on such planets as Mars.

Throughout the authors' studies, several problem areas were identified as needing attention to assure the practicality of IPMC for space applications. The authors addressed these issues and the results of their study are reported in this manuscript.

EAP ACTUATOR DRIVING DUST WIPER

Lessons learned from Viking and Mars Pathfinder missions indicate that the operation on Mars involves 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 efficiency of solar cells to produce power. To remove dust from surfaces one can use a similar mechanism as automobile windshield wipers. Contrary to conventional actuators, bending EAP has the ideal characteristics that are necessary to produce a simple, lightweight, low power wiper mechanism. Specifically, the IPMC responds to activation signals of about 0.3-Hz with a bending angle that can exceed 90 degrees span each way depending on the polarity. For dust cleaning from windows, it is necessary to place the wiper outside the viewing area and move it inward to clean the window. This necessitates the use of two wipers that are placed on opposite sides of the window as shown in Figure 1.

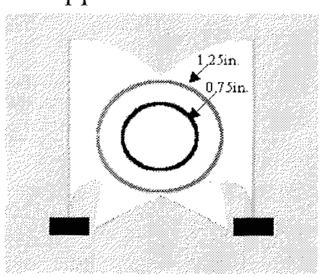

FIGURE 1: A schematic view showing the area that is covered by two bending EAP-actuators sweeping a window from two opposite sides.

To demonstrate the wiping capability, an IPMC was attached to a blade with a fiberglass brush and it was used to mechanically remove 20-μm dust particles that were sprinkled onto a glass plate (see bottom of Figure 2). Since this mechanism effectively addressed the critical issue of dust, the MUSES-CN mission selected it as a baseline technology for the Nanorover's infrared camera window. This mission is a joint effort of NASA and the NASDA (National Space Development Agency of Japan), which is scheduled to be launched from Kagoshima, Japan, in January 2002, to explore the surface of a small near-Earth asteroid. A photograph of the dust-wiper and a schematic view of the rover and the mission are shown in Figure 2.

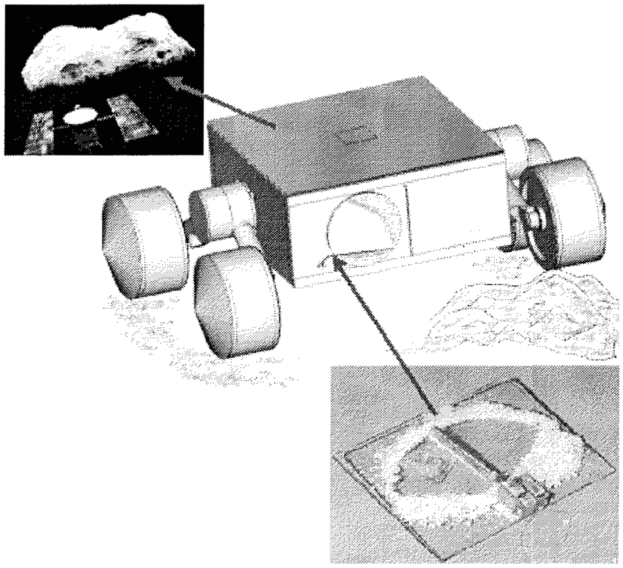

FIGURE 2: Schematic view of the EAP dust-wiper on the MUSES-CN's Nanorover (middle) and a photograph of a prototype EAP dust-wiper (right-bottom).

A unique ~100-mg wiper blade was constructed by ESLI (San Diego, CA) using a fiberglass brush and a graphite/ DuPont Kapton™ resin beam (see Figure 3). A 15 mm x 6 mm IPMC film was bonded to the ESLI blade with platinum electrode strips bonded on its other end to provide electrical excitation of the EAP wiper. Since mechanical wiping of a surface using a soft brush may not remove minute dust particles, which are smaller than the distance between the whiskers, a high voltage repulsion mechanism was introduced. The blade (beam and brush) was coated with gold and activated by 1-2-KV bias DC voltage, where as the EAP wiper was induced with 1-3V (Figure 3). The blade was processed at temperature of 623K (350°C) and tested at 77K demonstrating wide temperature durability. In an effort to bring the technology to space flight readiness the critical issues associated with the IPMC material as an actuators were addressed.

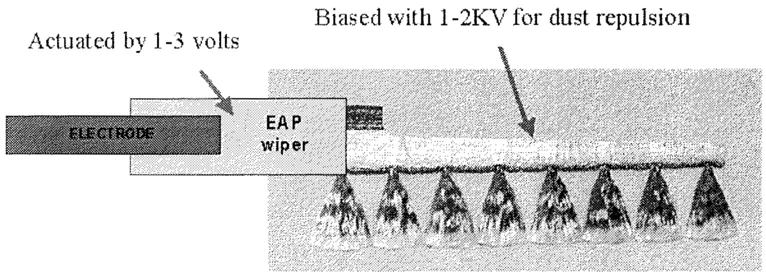

FIGURE 3: A schematic view of the EAP actuated dust-wiper

MODELING THE ACTUATOR

Design and prediction of the response of the IPMC dust wiper requires an effective analytical modeling of the material and its mechanical constraints. For this purpose, the Kanno-Tadokoro model was adopted using a gray box approach relating the experimental input-output data. The voltage applied to an actuator is transformed to current distribution through the membrane. The current generates distributed internal stress, which causes strain in the IPMC material and it is affected by its viscoelastic properties.

The resistances of surface layers and RC elements approximate the experimental voltage-current response as the electric property. The stress generation property and the viscoelasticity were expressed by an equation similar to the piezoelectric equation.

$$\sigma = D(s)\varepsilon - ei\frac{\omega_n^2 s}{s^2 + 2\varsigma\omega_n s + \omega_n^2}$$

Where: σ - internal stress; *D(s)* – mechanical characteristics including mass, damping and stiffness; ε- strain vector; *e* transformation tensor of stress generation; *i* – current through the actuator; and - ζ and ω_n delay parameters of the 2[nd] order.

It is natural that the current causes internal stress because the current hydrates the ionic flow. The 2nd order delay approximates the time delay until ionic distribution reaches equilibrium and internal stress is generated by swelling and electrostatic force. This equation was used to simulate the response of the IPMC actuators and in Figure 4a the result for 15-mm long 8-mm wide in shown. The strain near the electrodes clamp (fixture) is larger than the tip. Analysis of the model shows that current concentration near the electrodes causes imbalance of strain distribution. The response speed is faster near the electrodes because of the RC elements and therefore, it is better to design shorter actuator. The whole membrane deforms to roll in two dimensions. Deformation in the direction of width obstructs the wiper motion. When a 2mm long tip is constrained preventing it from deformation, the displacement is improved as shown in Figure 4b. Therefore, cross-piece design is important for efficiency.

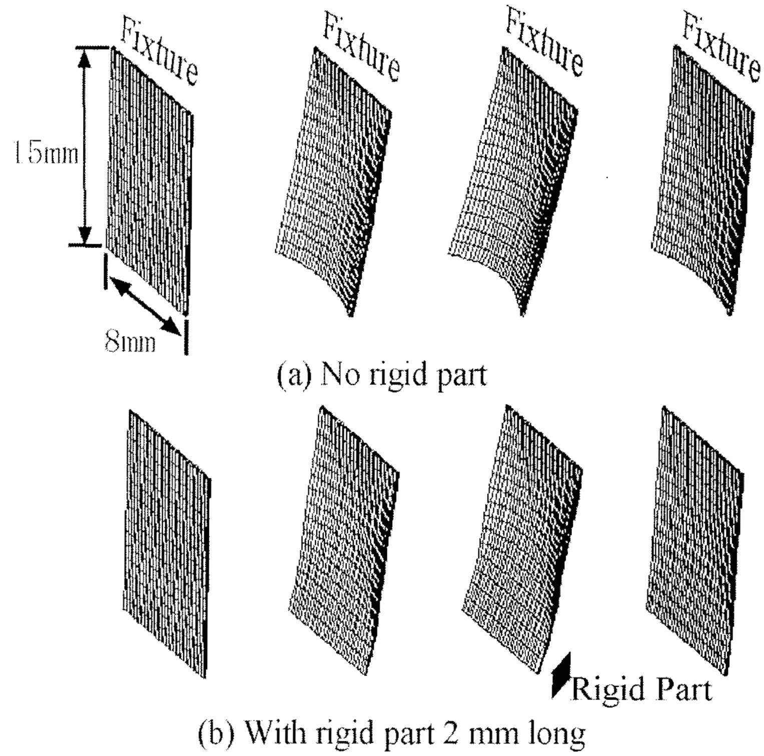

FIGURE 4: Simulation result of actuator motion.

IPMC AS A BENDING EAP ACTUATOR

Driving a dust wiper using EAP materials requires that material be capable of bending under electro-activation. As can be seen in the first issue of the WW-EAP Newsletter [Bar-Cohen, 1999a], several types of EAP materials can be made to bend under electrical excitation. The authors concentrated on the use of the ion exchange polymer membrane metal composite (IPMC) which has metal electrodes deposited on both sides. Two types of base polymers were used including Nafion® (perfluorosulfonate made by DuPont) and Flemion® (perfluorocaboxylate, made by Asahi Glass, Japan). Prior to using these polymers as EAP base materials, they were widely employed in fuel cells and production of hydrogen (hydrolysis). The operation as actuators is the reverse process of the charge storage mechanism associated with fuel cells. In the current study, Nafion® #117 was used with a thickness of 0.18-mm and perfluorocarboxylate films were used having thickness of 0.14-mm. Initial studies involved the use of Platinum as the metal electrodes however recent studies have shown that gold coating provides superior performance [Yoshiko, et al, 1998]. The gold layer was applied in 7-cycles resulting in a dendritic structure as shown in a cross section view in Figure 4. The counter cation consists of tetra-n-butylammonium or lithium and these two species showed significantly greater bending response than sodium, which was used earlier. Under less than 3 volts, such IPMC materials were shown to bend beyond a complete loop and the response follows the electric field polarity.

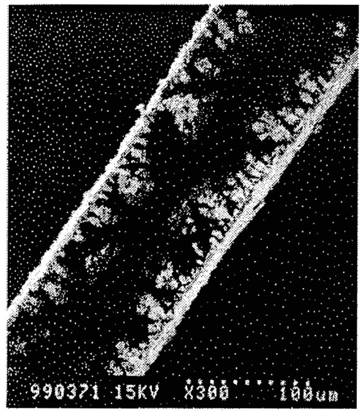

FIGURE 4: Perfluorocarboxylate membrane with tetra-n-butylammonium cation and 7 cycles of ion exchange and reduction (resulting dendritic growth) of the gold electrodes

When an external voltage is applied on an IPMC film, it causes bending towards the anode at a level that increases with the voltage, up until reaching saturation, as shown in Figure 5. 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 and the displacement diminishes as the frequency rises to several tens of Hz. The drive voltage level at which the bending displacement reaches saturation depends on the frequency and it is smaller at higher frequencies. The applied electrical current controls the movement of the film but the response is strongly affected by the water content of the IPMC serving as an ion transport medium.

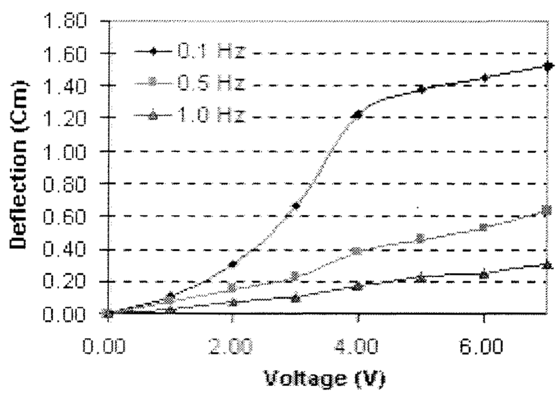

Figure 5: The response of the bending EAP to various voltage amplitudes at three different frequencies (data obtained for sodium base IPMC).

The authors addressed several issues that were determined critical to the application of IPMC (both the Nafion® and Flamion® base):

Film moisture: IPMC is highly sensitive to its moisture content. To maintain the moisture there is a need for a protective coating that acts as the equivalent of skin, otherwise the material stops to respond after few minutes of activation in dry conditions. Using an etching procedure and silicon coating, an IPMC film was shown to operate for about 4 months. This Dow Corning coating material allows operation in a wide range of temperatures with great flexibility and is durable under UV radiation. However, since the MUSES-CN mission requires operation over 3-years, the 4-month protection period is too short. Analysis of the cause of the degradation indicated that the silicon coating is water permeable and the rate is *$3000\ cm^3 \times 10^{-9}$ per sec/cm^2/cm* at STP and 1 cm•Hg pressure difference [Dow Corning, 1999]. Assuming 2 cm^2 electrode area with 0.1-mm thick silicone coating shows a water loss rate of ~40-50mg/24 hrs. This rate is significantly higher than observed for IMPC and it does not account for the IPMC electrode layers, however it indicates the severity of the issue. To overcome this limitation various alternative coatings are being considered including the use of a metallic Self-Assembled Monolayer as an overcoat.

Electrolysis: The wetness of IPMC and the introduction of voltages at levels above 1.03V introduce electrolysis during electro-activation causing degradation, heat and release of gasses. This issue raises a great concern since the emitted hydrogen accumulates under the protective coating and leads to blistering, which will rupture the coating due to the high vacuum environment of space. The use of tetra-n-butylammonium cations was shown to provide higher actuation efficiency leading to a reduction in the needed voltage and also to minimizing the electrolysis effect.

Operation in vacuum and low temperatures: In space the temperature can drop to significantly low levels and the ambient pressure is effectively vacuum. The ability to protect IPMC from drying allowed performing tests in vacuum and low temperatures. These tests showed that while the response decreases with temperature, as shown in Figure 6, a sizeable displacement was still observed at -140°C. This decrease can be compensated by an increase in voltage. It is interesting to point out that, at low temperatures, the response reaches saturation at much higher voltage levels.

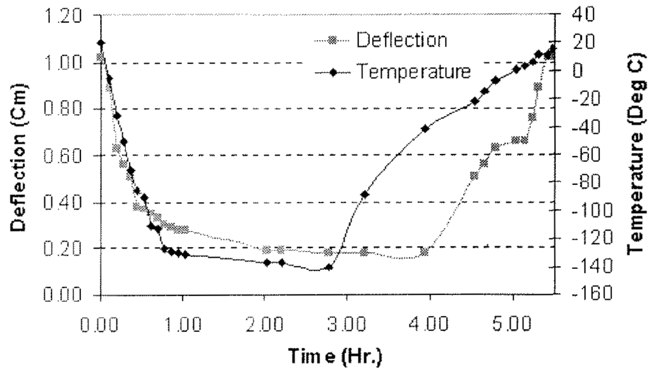

Figure 6: Deflection amplitude of sodium-base IPMC as a function of time and temperature.

Besides the need to address the low temperature issue, the material ability to sustain temperatures as high as +125°C is also necessary. For this purpose, several solvents with higher boiling points than water were examined for their potential use as a solvent for the IPMCs. One of the solvents examined was the equivalent of "antifreeze" in automobile radiators. Various solvents were considered and their effect on the swelling characteristics of Nafion® was investigated. Nafion® strips with an initial size of 5.8mm x 38.1mm were immersed in a series of solvents for a period of 4-days at ambient temperature and the effect on the mass and size were examined. The results are listed in Table 1 and show both swelling and increase in mass due to water absorption. Examination of IPMC films that were immersed for 24-hours in various solvents, including ethylene glycol, showed a significant reduction in the induced bending amplitude.

Low actuation force: Using thin IPMC with a thickness of 0.14-mm was found to induce a significant bending displacement. However, the induced force was found relatively small making it difficult for the wiper to overcome the electrical forces that are involved with the dust-repelling high-voltage. Further, even though the wiper blade is relatively light, weighing about 104-mg. This mass causes significant bending force resulting from gravity pressing the blade onto the window surface and constraining its movement. Alternative 0.18-mm thick film is currently being sought to provide the necessary force.

Permanent deformation under DC activation: Unfortunately, under a DC voltage IPMC strips do not maintain the actuation displacement and they retract after several seconds. Further, upon removal of the electric field an overshoot displacement occurs in the opposite direction moving slowly towards the steady state position leaving a permanent deformation. This issue was not resolved yet and would hamper the application of IPMC.

TABLE 1: Change in mass and size as a result of immersing Nafion® in various liquid media for 4-days at ambient temperature.

Solvent	Initial mass, g	Final mass, g	Change, %	Dimensions after soaking width x length (mm)
Water	0.0722	0.0838	16	5.8 x 43.0
N-methyl-2-pyrrolidinone (NMP)	0.0721	0.1124	56	6.4 x 50.8
Ethanol	0.0707	0.1113	57	6.4 x 50.8
Dimethylformamide (DMF)	0.0606	0.0974	61	6.4 x 44.5
Ethylene glycol	0.0720	0.1104	53	6.4 x 50.8
Ammonium hydroxide	0.0719	0. 0795	11	5.8 x 41.4

Challenges and solutions: To allow future design of EAP mechanisms actuated by IPMC, the challenges and solutions were summarized and are listed in Table 2. While most challenges seems to have been addressed two issues still pose a concern: the introduction of permanent deformation and the need for an effective protective coating. Unless these issues are effectively addressed the use of IPMC for planetary applications will be hampered.

TABLE 2: Challenges and identified solutions for issues regarding the application of IPMC.

Challenge	Solution
Fluorinate base - difficult to bond	Pre-etching
Sensitive to dehydration (~5-min)	Etching and coating
Electroding points cause leakage	Effective compact electroding method was developed
Off-axis bending actuation	Use of load (e.g., wiper) to constrain the free end
Most bending occurs near the poles	Improve the metal layer uniformity
Electrolysis occurs at >1.03-V in Na+/Pt	• Minimize voltage • Use IPMC with gold electrodes and cations based on Li^+, Perfluorocarboxylate with tetra-n-butylammonium
Survive -155°C to +125°C and operate at -125°C to + 60°C	IPMC was demonstrated to operate at -140°C
Need to remove a spectrum of dust sizes in the range of >3μm	• Use effective wiper-blade design (ESLI, San Diego, CA) • Apply high bias voltage to repel the dust
Reverse bending under DC voltage	Limit application to dynamic/controlled operations
Developed coating is permeable	• Alternative polymeric coating • Metallic Self-Assembled Monolayer overcoat
Residual deformation	Still a challenge
No established quality assurance	• Use short beam/film • Efforts are underway to tackle the critical issues

CONCLUSION

In recent years, electroactive polymers have emerged as actuators with great potential to enable unique mechanisms that can emulate biological systems. A study has taken place to adapt IPMC to planetary applications in an effort to develop a dust wiper for a mission to an asteroid. A series of challenges were identified as obstacles to the transition of such materials to space flight missions. Some of the key issues received effective solution, however key issues were identified that need further studies. These issues include the permanent deformation under DC activation and the water permeability of the developed protective coating. Another issue is the limited force that is induced by IPMC and the need to make a compromise between the bending displacement and the actuation force. Further studies are under way to overcome these obstacles and other EAP materials are also being considered as alternative bending actuators.

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