# CHAPTER 4

# Electroactive polymers as artificial muscles

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## Abstract

The potential for developing actuators with performance characteristics that rival that of muscle is increasingly becoming feasible with the emergence of effective electroactive polymers (EAP). Such polymers have many attractive characteristics including low weight, fracture tolerance, and pliability. EAP materials have functional similarities to biological muscles, including resilience, damage tolerance, and large actuation strains (stretching, contracting or bending). EAP-based actuators may be used to eliminate the need for gears, bearings, and other components that complicate the construction of robots and are responsible for high costs, high weight and premature failures. Furthermore, they can be configured into almost any conceivable shape, their properties can be engineered, and they can potentially be integrated with micro-electro-mechanical-system (MEMS) sensors to produce smart actuators. Visco-elastic EAP materials can potentially provide more life-like aesthetics, vibration and shock dampening, and more flexible actuator configurations. Exploiting the properties of artificial muscles may enable even the movement of the covering skin to define the character of the robots and provide expressiveness.

## 1 Introduction

Throughout history, humans have always sought to mimic the appearance, mobility, functionality, intelligent operation, as well as the decision-making and thinking process of biological creatures. This desire to imitate nature includes even mimicking the characteristics of humans, too. The field of biologically inspired technologies has the moniker biomimetics and it is increasingly introducing systems that are exhibiting realistic appearance and behavior. Robots, which verbally and facially express emotions and respond emotionally to such expressions, are being developed with greater capability and sophistication [Bar-Cohen and Breazeal, 2003]. Imagine a person walking towards you when suddenly you notice something weird about him he is not real but rather he is a robot. Your reaction would probably be "I

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can't believe it but this robot looks very much real," just as you would react to an artificial flower that is a good imitation. You may even proceed and touch the robot to check if your assessment is correct, but to your astonishment, as opposed to the case of artificial flowers, the robot may be programmed to respond verbally and/or physically to your touch. This science fiction scenario may become a reality as the current trend continues towards developing biologically inspired technologies and robots that appear and behave as human or animals. Beyond the mimicking of appearance and performance efforts are made to maximize the benefits of the biomimetic technologies by incorporating intelligence into the control of these robots.

Biology offers a great model for emulation in areas ranging from electromechanical tools, computer algorithms, materials science, mechanisms and information technology. Some of the implementations of this progress can be seen at many toy stores "near you", where toys appear and behave like biological creatures including dogs, cats, birds, frogs and others. Other benefits of this technology include prosthetic implants or human-aiding mechanisms that may be interfaced with the human brain to assist in hearing or seeing. Technology evolution led to such fields as artificial intelligence and artificial muscles, which are enabling us to consider making more realistic biomimetic intelligent robots.

Science fiction has contributed significantly to the expectations of this field. Human with bionic muscles is synonymous with a superhuman actor in movies or TV series. Driven by bionic muscles, the character is portrayed as capable of strength and speeds that are far superior to human. Recently, effective electroactive polymers (EAP) were developed that induce large strains (stretching, contracting or bending) [Bar-Cohen, 2001]. These materials have earned the moniker artificial muscles and may one day be used to make bionic muscles a reality or even make powerful robots that are actuated by these materials. As this technology evolves, novel biologically inspired mechanisms are expected to emerge with more realistic characteristics, including commercial products, medical devices and robots. EAP-based actuators may be used to eliminate the need for gears, bearings, and other components that complicate the construction of robots reducing their costs, weight and premature failures.

Generally, polymers with actuation capabilities that exhibit large displacement in response to other than electrical signal (e.g., chemical, thermal and light) were known for many years [Chapter 1, Bar-Cohen, 2001]. Initially, EAP received relatively little attention due to their limited actuation capability. However, in the last ten years, the view of the EAP materials has changed due to the introduction of effective new materials that surpassed the capability of the widely used piezoelectric polymer, PVDF2. Currently, efforts are underway to address the many challenges that are hampering the practical application of these materials. Various novel mechanisms and devices were already demonstrated including catheter steering element, robotic arm, gripper, loudspeaker, active diaphragm, and dust-wiper [Kornbluh and Pelrine, 2001; Kennedy et al., 2001; Hanson and Pioggia, 2001; Mavroidis et al., 2001; Jenkins 2001; and Chapter 21 in Bar-Cohen, 2001]. Other applications that are currently being considered include active Braille display for blind people and electroactive clothing, e.g., smart-bra with battery driven shape control. Combining photonic, transducing, sensing and other characteristics of polymers with EAP materials offers enormous potential for the development of multifunctional structures and biomimetic intelligent robots. Other aspects that can be inspired by biology and implemented using EAP can be the use of distributed sensors, multi-functionality and self-repair.

## 2 Nature as a biologically inspiring model

Evolution over millions of years made nature introduce solutions that are highly power-efficient, and imitating them offers potential improvements of our life and the tools we use. Human desire and capability to imitate nature, particularly biology, has continuously evolved, and with the improvement in the capability more difficult challenges are being considered. Initially, it was limited to making static copies of human and animals, in the form of statues and sculptures, as well as the development of tools to improve humans' life.

One of the early implementation of biologically inspired devices was the bicker of birds, which was adapted as a tool in the form of tweezers. More sophisticated inspirations include the development of aerodynamic structures and systems that use the shape of seeds. Trees disperse their seeds using various techniques where the use of aerodynamics allows them to self-propel with the aid of winds to carry the seeds to great distances. The shape of such seeds has inspired humans to produce objects that can be propelled in air and those have evolved to the boomerang, gliders, helicopter blades and various aerodynamic parts of aircrafts. In Figure 1, an example is shown of a winged seed of the Tipuana tipu (6.5-cm long), which is a street landscaping tree in such places as Southern California. Another plant that offered an inspiring design is the tumbleweed, suggesting a method of mobility that uses wind rather than a power-consuming mechanism. Since wind is blown throughout Mars, producing a spacecraft that imitates the tumbleweed offers an attractive option of designing a vehicle that can traverse great distances on Mars with a minimal use of power. It is not sufficient to mimic the appearance and performance of biology to maximize the benefits of the capability and a critical element of the developed robots is the need to incorporate intelligence into the system control.

Figure 1: A seed with aerodynamic shape for dispersion with the wind.

It is well known that the introduction of the wheel has been one of the most important invention that humans made allowing us to travel great distances and perform tasks that would have been otherwise impossible within the life time of a single human being. While wheel locomotion mechanisms allow great distances and speeds that are significantly beyond the capability of biological systems to be reached, they are subjected to great limitations with regards to traversing complex terrain with obstacles. Obviously, legged creatures can perform numerous functions that are far beyond the capability of an automobile. Producing legged robots is increasingly becoming an objective for robotic developers and considerations of using such robots for space applications are currently underway. Making miniature devices that can fly like a dragonfly, adhere to walls like gecko, adapt the texture, patterns, and shape of the surrounding as the octopus (that can reconfigure its body to pass thru very narrow tubing), process complex 3D images in real time, recycle mobility power for highly efficient operation and locomotion, self-replicate, self-grow using surrounding resources, chemically generate and store energy, and many other capabilities are some of the areas that biology offers a model for science and engineering inspiration. While many aspects of biology are still beyond our understanding, significant progress has been made.

### 2.1 Biological muscles as a model for EAP

Muscles are considered highly optimized systems since they are fundamentally the same for all animals and changes between species are small. Natural muscles are driven by a complex mechanism and are capable of lifting large loads with short response time (milliseconds). The operation of muscles depends on chemically driven reversible hydrogen bonding between two polymers, actin and myosin. Muscle cells are roughly cylindrical in shape, with diameters between 10 and 100 μm having a length of up to several centimeters. It is difficult to determine the performance of muscles and most measurements were made on large shell-closing muscles of scallops [Marsh et al., 1992]. A peak stress of 150 to 300 KPa is developed at a strain of about 25%, while the maximum power output is 150 to 225 W/kg. The average power is about 50 W/kg with an energy density of 20 to 70 J/kg that decreases when the speed is increased. Although muscles produce linear forces, all motions at joints are rotary. Therefore, the strength of an animal is not just muscle force, but muscle force modified by the mechanical advantage of the joint [Alexander, 1988], which usually varies with joint rotation. The mechanical energy is provided by a chemical free energy of a reaction involving adenosine triphosphate (ATP) hydrolysis. The release of $Ca^{2+}$ ions is responsible for turning on and off the conformational changes associated with muscle striction.

### 2.2 Artificial muscles

In spite of the success in making robots that mimic biology, there is still a large gap between the performance of robots and nature creatures. The required technology is multidisciplinary and has many aspects, including the need for actuators that emulate muscles. The potential for such actuators is increasingly becoming feasible with the emergence of effective electroactive polymers (EAP) [Bar-Cohen, 2001]. These materials have functional similarities to biological muscles, including resilience, damage tolerance, and large actuation strains (stretching, contracting or bending). EAP-based actuators may be used to eliminate the need for gears, bearings, and other components that complicate the construction of robots and are responsible for high costs, weight and premature failures. Visco-elastic EAP materials can potentially provide more life-like aesthetics, vibration and shock dampening, and more flexible actuator configurations. Exploiting the properties of artificial muscles may enable even the movement of the covering skin to define the character of the robots and provide expressivity.

Polymers have many attractive characteristics including low weight, fracture tolerance, and pliability. Furthermore, they can be configured into almost any conceivable shape and their properties can be tailored to suit a broad range of requirements. In the last decade, new polymers have emerged that respond to electrical stimulation with a significant shape, or size change and this progress has added an important capability to these materials. Generally, EAP materials can induce strains that are as high as two orders of magnitude greater than the striction-limited, rigid and fragile electroactive ceramics (EAC). Furthermore, EAP materials are superior to shape-memory alloys (SMA) in higher response speed, lower density, and greater resilience. This capability of the electroactive polymers (EAP) attracted the attention of engineers and scientists from many different disciplines. Practitioners in biomimetics are particularly excited about these materials since the artificial-muscle aspect of EAPs can be applied to mimic the movements of animals and insects. In the foreseeable future, robotic mechanisms actuated by EAPs will enable engineers to create devices previously imaginable only in science fiction.

## 3 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 with fixed end and a mass attached to the free-end and then being charged and discharged [Roentgen, 1880]. Sacerdote [1899] followed this experiment with a formulation of the strain response to electric field activation. Further milestone progress was recorded only in 1925 with the discovery of a piezoelectric polymer, called electret, when carnauba wax, rosin and beeswax were solidified by cooling while subjected to a DC bias field [Eguchi, 1925]. Generally, there are many polymers that exhibit volume or shape change in response to perturbation of the balance between repulsive intermolecular forces, which act to expand the polymer network, and attractive forces that act to shrink it. Repulsive forces are usually electrostatic or hydrophobic in nature, whereas attraction is mediated by hydrogen bonding or van der Waals interactions. The competition between these counteracting forces, and hence the volume or shape change, can be controlled by subtle changes in parameters such as solvent, gel composition, temperature, pH, light, etc. The type of polymers that can be activated by non-electrical means include: chemically activated, shape-memory polymers, inflatable structures, including McKibben Muscle, light-activated polymers, magnetically activated polymers, and thermally activated gels [Bar-Cohen, 2001].

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. The convenience and practicality of electrical stimulation and technology progress led to a growing interest in EAP materials. Following the 1969 observation of a substantial piezoelectric activity in PVDF2 [Chapter 1, Bar-Cohen, 2001], investigators started to examine other polymer systems, and a series of effective materials have emerged. The largest progress in EAP materials development has occurred in the last ten years where effective materials that can induce over 300% strains have emerged [Kornbluh and Pelrine, 2001].

## 4 The two major categories of EAP materials

EAP can be divided into two major categories based on their activation mechanism: electronic and ionic (Table 1). The electronic EAP, such as electrostrictive, electrostatic, piezoelectric, and ferroelectric, are driven by Coulomb forces. This type of EAP material can be made to hold the induced displacement while activated under a DC voltage, allowing them to be considered for robotic applications. These materials have a greater mechanical energy density and they can be operated in air with no major constraints. However, in spite of recent developments in making composite EAP, most of the electronic EAP materials are requiring high activation fields (>100 V/μm) that may be close to the breakdown level.

In contrast to the electronic EAP, ionic EAP are materials that involve mobility or diffusion of ions and they consist of two electrodes and electrolyte. The activation of the ionic EAP can be made by as low as 1 to 2 V and mostly a bending displacement is induced. Examples of ionic EAP include gels, polymer–metal composites, conductive polymers, and carbon nanotubes. Their disadvantages are the need to maintain wetness and they pose difficulties to sustain constant displacement under activation of a DC voltage (except for conductive polymers).

The induced displacement of both the electronic and ionic EAP can be designed geometrically to bend, stretch or contract. Any of the existing EAP materials can be made to bend with a significant bending response, offering an actuator with an easy to see reaction (see example in Figure 2). However, bending actuators have relatively limited applications due to the low force or torque that can be induced. EAP materials are still custom made mostly by researchers and they are not readily available commercially. To help in making them widely available, the author established a website that provides fabrication procedures for the leading types of EAP materials [http://ndeaa.jpl.nasa.gov/nasa-nde/lommas/eap/EAP-recipe.htm].

Table 1: List of the leading EAP materials.

| **Electronic EAP** | **Ionic EAP** |
|---|---|
| Dielectric EAP | • Carbon nanotubes (CNT) |
| Electrostrictive graft elastomers | • Conductive polymers (CP) (see Figure 2) |
| Electrostrictive paper | • Electrorheological fluids (ERF) |
| Electro-viscoelastic elastomers | • Ionic polymer gels (IPG) |
| Ferroelectric polymers | • Ionic polymer metallic composite (IPMC) |
| Liquid crystal elastomers (LCE) | |

## 5 Need for enhanced EAP technology infrastructure

Electroactive polymers can be easily formed in various shapes, their properties can be engineered and they can potentially be integrated with micro-electro-mechanical-system (MEMS) sensors to produce smart actuators. As mentioned earlier, their most attractive feature is their ability to emulate the operation of biological muscles with high fracture tolerance, large actuation strain and inherent vibration damping. Unfortunately, the EAP materials that have been developed so far are still exhibiting low conversion efficiency, are not robust, and there are no standard commercial materials available for consideration in practical applications. In order to be able to take these materials from the development phase to application as effective actuators, there is a need for an established EAP infrastructure (Chapter 1, Bar-Cohen 2001). Effectively addressing the requirements of the EAP infrastructure involves developing adequate understanding of EAP materials' behavior, as well as the availability of standard processing and characterization techniques.

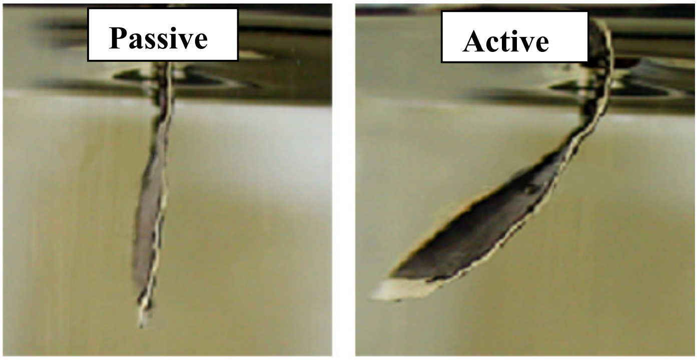


Figure 2: Conductive EAP actuator is shown bending under stimulation of 2 V, 50 mA.

Enhancement of the actuation force studies is sought through improvement of the understanding of the basic principles using computational chemistry models, comprehensive material science, electro-mechanics analytical tools and material-processing techniques. Efforts are underway to gain a better understanding of the parameters that control the EAP electro-activation force and deformation. The processes of synthesizing, fabricating, electroding, shaping and handling are being refined to maximize the EAP materials actuation capability and robustness. Methods of reliably characterizing the response of these materials are being developed, and efforts are being made to establish a database with documented material properties in order to support design engineers that are considering the use of these materials and towards making EAP actuators of choice. Various configurations of EAP actuators and sensors are being studied and modeled to produce an arsenal of effective smart EAP-driven systems. In the last four years, significant international effort has been made to address the various aspects of the EAP infrastructure and to tackle the multidisciplinary issues [Bar-Cohen, 2001]. Currently, many researchers and engineers are addressing each of the elements of the infrastructure. The progress has been documented in the conference proceedings of the SPIE and MRS conferences that are dedicated to the topic of electroactive polymer actuators and devices [Bar-Cohen, 1999 and subsequent years; and Zhang et al. 1999]. The author believes that an emergence of a niche application that addresses a critical need will significantly accelerate the transition of EAP from novelty to actuators of choice. In such case, the uniqueness of these materials will be exploited and commercial products will emerge in spite of the current limitations of EAP materials.

## 6 Present technology, future possibilities and potentials

Mimicking nature would immensely expand the collection and functionality of the robots allowing performance of tasks that are impossible with existing capabilities. As technology evolves, a great number of biologically inspired robots actuated by EAP materials emulating biological creatures is expected to emerge. The challenges to making such a robot are presented in Figure 3, where a robot dog is shown to hop and express emotion. Both tasks are easy for human to do but are extremely complex to incorporate into a robot.

To promote the development of effective EAP actuators, which could impact future robotics, toys and animatronics, two platforms were developed and were made available to the author for the support of the worldwide development of EAP. These platforms include an android head that can make facial expressions and a robotic hand with activatable joints (Figure 4). The head can be made to move the eyes and the lips, whereas the hand allows moving the index finger. At present, conventional electric motors are producing the required deformations to make relevant facial expressions of the android. Once effective EAP materials are chosen, they will be modeled into the control system in terms of surface-shape modifications and control instructions for the creation of the desired facial expressions. The robotic hand (Figure 4) is equipped with wire-based tandems and sensors for the operation of the various joints mimicking a human hand. The index finger of this

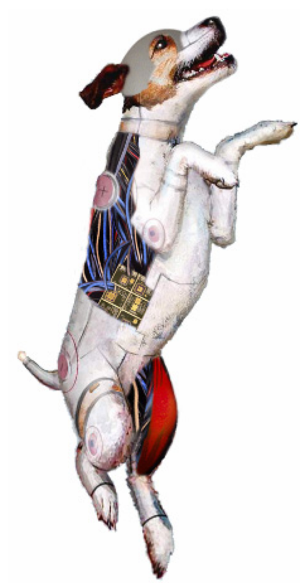

Figure 3: Biomimetic robot (the dog image is courtesy of D. Hanson, University of Texas at Dallas).

hand is currently being driven also by conventional motors in order to establish a baseline and they would be substituted by EAP when such materials are developed as effective actuators.

The easy capability to produce EAP in various shapes and configurations can be exploited using such methods as stereolithography and ink-jet printing techniques. A polymer can be dissolved in a volatile solvent and ejected drop-by-drop onto various substrates. Such processing methods offer the potential of making robots in full 3D details including EAP actuators, allowing rapid prototyping and quick mass production [Chapter 14 in Bar-Cohen, 2001]. A possible vision for such technology can be the fabrication of insect-like robots that can be made to fly and pack themselves into a box to be ready for shipping once they are made. Another example can be the use of a movie script to produce the needed robots and they can be modified rapidly as needed for the evolving script. Making insect-like robots could help inspection of hard-to-reach areas of aircraft structures where the creatures can be launched to conduct the inspection procedures and download the data upon exiting the structure.

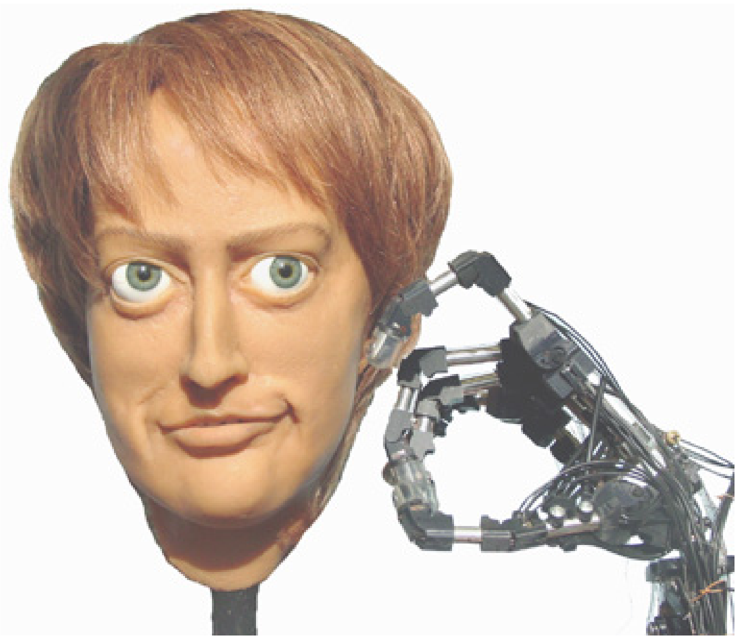

Figure 4: EAP platform for demonstration of EAP actuators.

Left - An android head that makes facial expressions (Photographed at JPL. This head was sculptured by D. Hanson, University of Texas at Dallas and instrumented by G. Pioggia, University of Pisa, Italy).
Right – Biologically inspired robotic hand (Photographed at JPL. This hand was made by G. Whiteley, Sheffield Hallam U., UK. The actuators were installed at JPL by G. Pioggia – University of Pisa, Italy).

### 6.1 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 six 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 and Mussa-Ivaldi, 2000] enabled this possibility where electrodes have been connected to the brain of a monkey, and using brain waves the monkey was able 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.

## 7 Lesson learned using IPMC and dielectric EAP

To understand the challenges that are involved with employing EAP materials as actuators, the experience at the Jet Propulsion Laboratory (JPL) that was acquired in seeking applications for IPMC is reviewed herein. The author and his team made extensive efforts to develop effective planetary applications for iuonic polymer/metal composite (IPMC), and a number of issues were identified that hampered its immediate application. While the micro- and macro-electromechanical behavior is still not fully understood, methodic modeling and experimental studies have significantly contributed to the knowledge base [Nemat-Nasser and Thomas, 2001].

Space applications are among the most demanding in terms of the harshness of the operating conditions, requiring a high level of robustness and durability. For an emerging technology, the requirements and challenges associated with making hardware for space flight are very difficult to overcome. However, since such applications usually involve producing only small batches they can provide an important avenue for introducing and experimenting with new actuators and devices. This is in contrast with commercial applications, for which issues of mass production and cost per unit can be critical to the transition of the technology to practical use.

Between 1995 and 1999, under the author's lead, a NASA study took place with the objective of improving the understanding and practicality of EAP materials and identifying planetary applications. The materials that were investigated include IPMC and dielectric EAP, which was named ESSP (electro-statically stricted polymer), and they were used as bending and longitudinal actuators, respectively. The devices that were developed include a dust-wiper, gripper, robotic arm, and miniature rake. The dust-wiper (Figure 5) received the most attention and it was selected as the baseline in the MUSES-CN mission as a component of the Nanorover's optical/IR window.

The use of IPMC was investigated jointly with NASA LaRC, Virginia Tech, Osaka National Research Institute and Kobe University from Japan. The team used a perfluorocarboxylate-gold composite with two types of cations, tetra-n-butylammonium and lithium. An IPMC was used as an actuator to wipe the window with the aid of a unique 104 mg blade having a gold-plated fiberglass brush (Figure 6), which was developed by ESLI (San Diego, CA). When subjecting this blade to a high voltage bias (1 to 2 KV) it repels dust and thus augments the brushing mechanism provided by the blade. A photographic view of the repelled dust and the wiper is shown in Figure 6. Tests showed that the heat losses associated with the activation of the IPMC in vacuum allow the actuator to respond at temperatures as low as $-100^{o}$C.

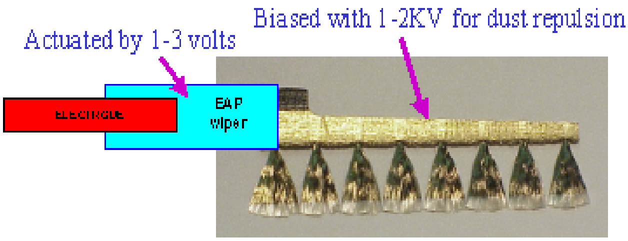


Figure 5: Combined schematic and photographic view of the EAP dust wiper.


Figure 6: A view of the dust wiper activated with high voltage to repel dust

The sensitivity of IPMC to dehydration and the need to maintain its ionic content were addressed using a protective coating (Dow Corning 92-009). This coating was applied after the IPMC was etched to make it amenable to bonding. The application of such a protective coating emulates the role of biological skin that protects and encapsulates the blood and other life-essential body fluids. Experiments have shown that this coating allows the operation of IPMC in air, but the longest period that a protected sample maintained response was about four months. Analysis indicates that the selected coating material is water permeable, limiting the potential of long-term operation in dry conditions. Alternatives, such as the use of multi-layered coatings, possibly consisting of metallic self-assembled monolayering, were considered but the preliminary results were not encouraging. Complication arises when subjecting IPMC actuators to voltages above 1.23V, as a result of the electrolysis that takes place. This process raises concern since hydrogen blisters are formed under the protective coating and are expected to rupture the coating, particularly since there is an extreme vacuum on the asteroid.

Under DC activation, IPMC bends relatively quickly (0.1 to 1 seconds, depending on the size of the cations) followed by a slow recoiling with a permanent deformation [Nemat-Nasser, and Thomas, 2001]. This recoiling can be a serious issue, particularly with $Na^+$ cations for which there is a bending drift in the opposite direction when the activating voltage is maintained constant. The application of IPMC is further complicated by the fact that permanent deformation is also encountered after intermittent actuation and in its current state it cannot be relaxed by electrical activation. This issue is viewed as a challenge that is not resolved yet and may be addressed by an optimal selection of the ionic content of the IPMC material (Table 2).

Table 2: Challenges and identified solutions associated with the application of IPMC.

| Challenge | Potential Solution |
|---|---|
| Fluorinate base which is difficult to bond | Etching the surface makes it amenable to bonding |
| Extremely sensitive to dehydration | Apply protective coating over the surface of the IPMC |
| Off-axis bending actuation | Constrain the free end and use a high ratio of length/width |
| Operate at low and high temperatures | The issue of extreme temperatures is a major concern. Operating a coated IPMC in vacuum allowed response at $-100^{o}$C. |
| Removal of submicron dust | Use effective wiper-blade design and high bias voltage |
| Reverse bending drift under DC voltage | Limit the operation to cyclic activation to minimize this effect, and use cations such as $Li^+$ rather than $Na^+$. |
| Residual deformation particularly after intermittent activation | It occurs mostly after DC or pulse activation and it remains a challenge. |
| Protective coating is permeable | Develop alternative coating, possibly using multiple layers |
| Electrolysis occurs at >1.23V | Use efficient IPMC that requires low actuation voltage |
| Difficulties to assure material reproducibility | Still a challenge. May be possible to overcome using mass production and protective coating. |
| Degradation with time due to loss of ions to the host liquid | Use effective coating or immersion in electrolyte with enriched cation content of the same species as in the IPMC. |

## 8 Summary and outlook

Technologies that allow developing biologically inspired systems are increasingly emerging allowing us to consider the design and construction of biomimetic intelligent robots. EAP materials have emerged with great potential, enabling the development of unique biologically inspired devices. Legged, finned or winged robots may be developed using electroactive polymers that will enable combinations of locomotion techniques including walking, hopping, swimming, diving, crawling, flying, etc., with selectable behavior and performance characteristics. Such robots that are driven by artificial muscles and controlled by artificial intelligence would allow making engineering reality out of what is considered science fiction today.

Using effective EAP actuators to mimic nature would immensely expand the collection and functionality of robots that are currently available. Important additions to this capability could be the application of tele-presence combined with virtual reality using haptic interfaces. Such capabilities are expected to significantly change future robots; however, there is a need for significant research and development to enhance the robustness of EAP and their efficiency. These efforts will require advancement in related computational chemistry models, comprehensive material science, electro-mechanics analytical tools, and improved material-processing techniques. In addition to developing better actuators, a discipline of visco-elastic engineering and control strategies will need to be developed to supplant the traditional engineering of rigid structures.

Figure 7: Grand challenge for the development of EAP-actuated robotics.

There are still many challenges, but the recent trend of international cooperation, the greater visibility of the field and the surge in funding of related research projects are offering great hope. To assist in the development of effective biologically inspired robots, an android head and robotic hand were made available to the author to offer them as platforms for the demonstration of internationally developed actuators. The author's arm-wrestling challenge – a match between EAP-actuated robots and a human opponent (Figure 7) – highlights the potential of this technology. Progress towards winning this arm wrestling match will lead to exciting new generations of robots and is expected to change our daily life. Such changes may include the possibility of robots becoming a household assistant and intelligent companion possibly substituting the dog as our "best friend".

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