

# Electroactive Polymers (EAP) as actuators for potential future planetary mechanisms

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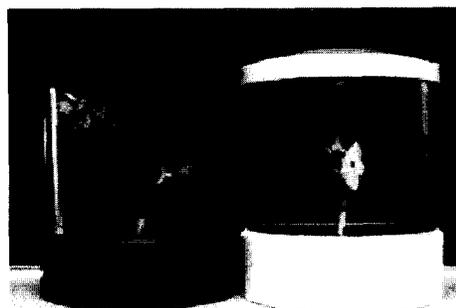
## Abstract

*In the last fifteen years a series of Electroactive Polymers (EAP) materials have emerged that exhibit a significant shape or size change in response to electrical stimulation. These materials have the closest response similarity to biological muscles enabling to engineer novel capabilities that were considered until recently science fiction ideas. Initially, EAP received relatively little attention due to their limited actuation capability. Recent progress led to dramatic improvements in the capability of these materials and 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 robot fish, catheter steering element, robotic arm, gripper, loudspeaker, active diaphragm, and dust-wiper. For developers of future planetary mechanisms the flexibility, fracture toughness, low mass and low power requirements of these materials are offering numerous advantages. This paper provides background about these materials and it includes a review of the state of the art, challenges and potential applications of these materials for future space missions.*

## 1. Introduction

Actuators (motors, etc.) are used in many space applications including release mechanisms, antenna and instrument deployment, positioning devices, aperture opening and closing devices, real-time compensation for thermal expansion in space structures, etc. Increasingly, there are requirements to reduce the size, mass, and power of these devices, and to lower the cost to NASA. Also, there is a need to develop effective capabilities that can support the challenges to in-situ analysis, sample return, human exploration of the universe and many other complex tasks. Electroactive ceramics (e.g., piezoelectric and electrostrictive) are effective, compact actuation materials and they were used to replace electromagnetic motors for the articulation of spacecraft components (e.g. WF/PC II). However, while these materials are capable of delivering large

forces, they produce a relatively small displacement on the order of magnitude of fraction of a percent. Also, these materials are fragile and are not practical for articulation of gossamer type configurable structures.



**FIGURE 1:** The first commercial EAP product - a fish robot (courtesy of Eamex, Japan)

The emergence of effective electroactive polymers (EAP) that can induce large displacements have made these materials an attractive alternative to motors and conventional electroactive materials [Bar-Cohen, 2001 and 2004]. These materials have functional similarities to biological muscles, including resilience, damage tolerance, and large actuation strains (stretching, contracting or bending). They can be used to make mechanical devices and robots with no traditional components like gears, and bearings, which are responsible to their high costs, weight and premature failures. Moreover, EAP materials can be used to make biomimetic devices that otherwise may have been impossible to engineer and considered science fiction [Bar-Cohen and Breazeal, 2003; and Bar-Cohen, 2004a]. One such commercial product has already emerged in Dec. 2002 is a form of a Fish-Robot (Eamex, Japan). An example of this Fish-Robot is shown in Figure 1. It swims without batteries or a motor and it uses EAP materials that simply bend upon stimulation. For power it uses inductive coils that are energized from the top and bottom of the fish tank. This fish represents a major milestone for the field, as it is the first reported commercial product to use electroactive polymer actuators.

## 2. Nature as a biologically-inspiring model

Evolution over millions of years made nature to introduce solutions that are highly effective and power-efficient and imitating them offers enormous potential to future NASA missions. The desire and capability to imitate nature and particularly biology has continuously evolved and with the improvement in technology more difficult challenges are being considered. Probably, one of the early implementation of biologically inspired devices was the beak of birds, which was adapted as a tool in the form of tweezers and tongs. 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 wind to carry the seeds to great distances. The shape of such seeds has inspired human 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.

The introduction of the wheel has been one of the most important inventions that human made allowing 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 reaching great distances and speeds, wheeled vehicles 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 (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 as a model for science and engineering inspiration. While many aspects of biology are still beyond our understanding and capability, significant progress has been made.

## 3. EAP as artificial muscles

One of the key aspects of making biologically inspired robots is the development of actuators that allow emulating the behavior and performance of real

muscles. The potential of such actuators is continually growing with the introduction of more effective EAP materials [Bar-Cohen, 2001 and 2004].

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 [Chapter 1 in Bar-Cohen, 2001]. Polymers that can be stimulated chemically 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. 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, which was 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]. Following the 1969 observation of a substantial piezoelectric activity in PVF2 [<http://www.ndt.net/article/yosi/yosi.htm>], 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 fifteen years where effective materials that can induce over 300% strains have emerged [Kornbluh and Pelrine, 2001].

EAP can be divided into two major groups based on their activation mechanism including ionic and electronic (Table 1). The electronic EAP, such as

electrostrictive, electrostatic, piezoelectric, and ferroelectric, are driven by Coulomb forces. This type of EAP materials 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, the electronic EAP require a high activation fields ( $>10\text{-V}/\mu\text{m}$ ) 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 1-2 Volts 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 various EAP materials have advantages and disadvantages (see Table 2) that determine both their applicability and practical use.

**TABLE 1:** List of the leading EAP materials

<b>Electronic EAP</b>	<b>Ionic EAP</b>
Dielectric EAP Electrostrictive Graft Elastomers Electrostrictive Paper Electro-Viscoelastic Elastomers Ferroelectric Polymers Liquid Crystal Elastomers (LCE)	<ul style="list-style-type: none"> <li>• Carbon Nanotubes (CNT)</li> <li>• Conductive Polymers (CP) (see Figure 2)</li> <li>• ElectroRheological Fluids (ERF)</li> <li>• Ionic Polymer Gels (IPG)</li> <li>• Ionic Polymer Metallic Composite (IPMC)</li> </ul>

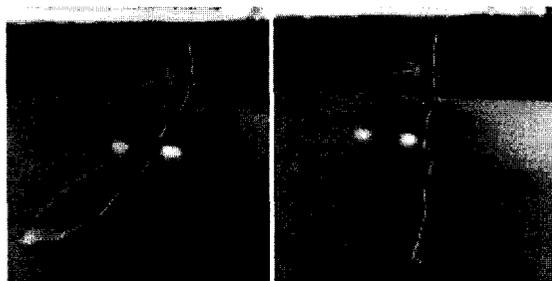
**TABLE 2:** Summary of the advantages and disadvantages of the two major EAP groups.

<b>EAP type</b>	<b>Advantages</b>	<b>Disadvantages</b>
Electronic EAP	<ul style="list-style-type: none"> <li>• Can operate in room conditions for a long time</li> <li>• Rapid response (msec levels)</li> <li>• Can hold strain under dc activation</li> <li>• Induces relatively large actuation forces</li> </ul>	<ul style="list-style-type: none"> <li>• Requires high voltages (<math>\sim 150\text{ MV/m}</math>). Recent development allowed for (<math>\sim 20\text{ MV/m}</math>)</li> <li>• Glass transition temperature is inadequate for low-temperature actuation tasks and, in the case of Ferroelectric EAP, high temperature applications are limited by the Curie temperature</li> <li>• Due to associated electrostriction effect, a monopolar actuation is produced independent of the voltage polarity.</li> </ul>
Ionic EAP	<ul style="list-style-type: none"> <li>• Produces large bending displacements</li> <li>• Requires low voltage</li> <li>• Natural bi-directional actuation that depends on the voltage polarity.</li> </ul>	<ul style="list-style-type: none"> <li>• Except for CPs and NTs, ionic EAPs do not hold strain under dc voltage</li> <li>• Slow response (fraction of a second)</li> <li>• Bending EAPs induce a relatively low actuation force</li> <li>• Except for CPs, it is difficult to produce a consistent material</li> <li>• In aqueous systems, EAP suffer electrolysis at <math>&gt;1.23\text{ V}</math></li> <li>• To operate in air requires attention to the electrolyte.</li> <li>• Low electromechanical coupling efficiency.</li> </ul>

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 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://ndea.jpl.nasa.gov/nasa-nde/lommas/eap/EAP-recipe.htm>. To help further, the author compiled inputs from companies that make EAP materials, and prototype devices or provide EAP related processes

and services. The input was documented in a handy table that is posted on a link to the WW-EAP website: <http://ndea.jpl.nasa.gov/nasa-nde/lommas/eap/EAP-material-n-products.htm>.



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

Unfortunately, the 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 to establish an adequate EAP infrastructure [Chapter 1 of Bar-Cohen, 2001 and 2004]. Effectively addressing the requirements of the EAP infrastructure involves developing adequate understanding of EAP materials' behavior, as well as processing and characterization techniques.

The technology of artificial muscles is still in its emerging stages but the increased resources, the growing number of investigators conducting research related to EAP, and the improved collaboration among developers, users, and sponsors are leading to rapid advances in this field. In 1999, in an effort to promote worldwide development towards the realization of the potential of EAP materials the author posed an armwrestling challenge. A graphic rendering of this challenge is illustrated in Figure 3. In posing this challenge, the author sought to see an EAP activated robotic arm win against human in a wrestling match to establish a baseline for the implementation of the advances in the development of these materials. Success in wrestling against humans will enable capabilities that are currently considered impossible. It would allow applying EAP materials to improve many aspects of our life where some of the possibilities include effective implants and prosthetics, active clothing, realistic biologically inspired robots as well as fabricating products with unmatched capabilities and dexterity. Recent advances in understanding the behavior of EAP materials and the improvement of their efficiency led

to the possibility that in the coming years an EAP actuated arm will win such a wrestling match. The most notable milestone is the EAP driven arm that was made by Environmental Robots Incorporated (ERI), New Mexico, and presented at the EAP-in-Action Session of this 2004 EAPAD Conference. This wrestling arm (see Figure 4) has the size and the configuration of an average human arm and it is driven by conductive polyacrylonitrile (PAN-C) EAP. This EAP material was shown experimentally to produce close to 200% linear strain and pulling strength that is higher than human muscles [Schreyer et al., 2000].

To plan the first international arm-wrestling competition efforts are currently underway to establish the rules for the competition towards possibly holding it as part of the SPIE's Annual International EAPAD (EAP Actuators and Devices) Conferences in San Diego, California, USA. Success in developing such an arm will lead in decades from now to the possible use of EAP to replace damaged human muscles, i.e., making "bionic human." A remarkable contribution of the EAP field would be to see one day a handicapped person jogging to the grocery store using this technology.



**FIGURE 3:** Grand challenge for the development of EAP actuated robotics.



**FIGURE 4:** A wrestling arm with size and configuration of an average human arm was recently developed. (Courtesy of M. Shahinpoor, Environmental Robots Incorporated, New Mexico)

In recognition of the need for international cooperation among the developers, users, and potential sponsors, the author organized the first EAP conference on March 1–2, 1999, through The International Society for Optical Engineering (SPIE) as part of the Smart Structures and Materials Symposium [Bar-Cohen, 1999]. This conference was held in Newport Beach, California, USA, and was the largest ever on this subject, marking an important milestone. This conference turned the spotlight onto these emerging materials and their potential. Following this success, a Materials Research Society (MRS) conference was initiated to address fundamental issues related to the material science of EAP [Zhang et al., 1999]. In recent years, there has been increasing number of organizations and technical societies who are organizing workshops, meetings and conferences with sessions on EAP. The SPIE's EAPAD conferences are now organized annually and have been steadily growing in number of presentations and attendees. In addition to the conferences, there is a website called the WorldWide EAP (WW-EAP) Webhub that archives related information and links to homepages of EAP research and development facilities worldwide [<http://ndeaa.jpl.nasa.gov/nasa-nde/lommas/eap/EAP-web.htm>]. Since June 1999, the semi-annual WW-EAP Newsletter has been published with short synopses from authors worldwide providing a snapshot of their advances. This Newsletter is published electronically and its issues are accessible via the above mentioned WW-EAP webhub [<http://ndeaa.jpl.nasa.gov/nasa-nde/lommas/eap/WW-EAP-Newsletter.html>]. Further, the author edited a reference book on EAP that has been published in 2001 [Bar-Cohen, 2001] with its 2nd edition is expected to be published before the 2004 EAPAD Conference [Bar-Cohen, 2004]. This book provides a comprehensive documented reference, technology user's guide, and tutorial resource, with a vision for the future direction of this field. It covers the field of EAP from all its key aspects, i.e., its full infrastructure, including the available materials, analytical models, processing techniques, and characterization methods.

#### **4. Considerations of planetary applications of EAP**

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, potential consumer demand and cost per unit can be critical to the transfer of technology to practical use.

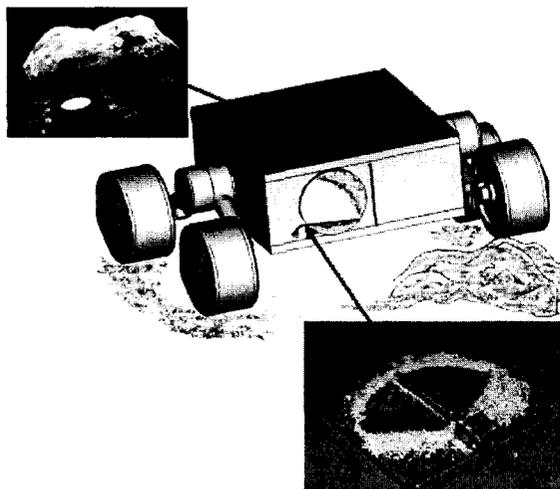
Between 1995 and 1999, under the author's lead, a NASA study took place with the objective of improving the understanding and practicality of EAP materials and identifying planetary applications. In this task the issues of making, testing, operating and applying EAP materials for potential use in future NASA missions was investigated [Chapters 1, 6, 12, 13, 20 and 21 of Bar-Cohen, 2001 and 2004]. Under this task, the materials that were investigated include IPMC and dielectric EAP 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.

##### **4.1 Dust wiper for the Nano-Rover**

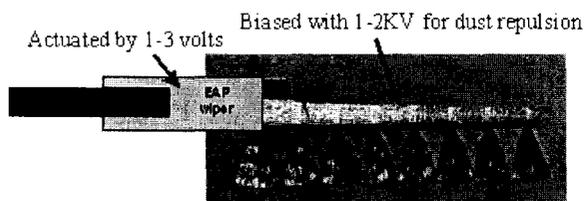
The dust wiper (Figure 5) that was developed under the above task received the most attention and was selected as baseline in the MUSES-CN mission as a component of the Nanorover's optical/IR window. Selection as baseline means that the specific mechanism, component or device is considered part of the mission hardware. The MUSES-CN mission was a joint NASA and NASDA (National Space Development Agency of Japan) mission that was scheduled for launch in January 2002, from Kagoshima, Japan, to explore the surface of a small near-Earth asteroid. The MUSES-CN mission itself was cancelled due to budget constraints but it gave the field of EAP an important opportunity and brought the field to the public spotlight. The challenges to the application of IPMC and the required cost to overcome these challenges hampered the inclusion of the dust wiper in the final hardware configuration of this mission before its cancellation.

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 novel 104-mg blade having a gold-plated fiberglass brush (Figure 6), which was developed by ESLI (San Diego, California). When this blade is subjected to high voltage (1–2 KV), it repels dust, thus augmenting the brushing mechanism provided by the

blade. A photographic view of the repelled dust and the wiper are shown in Figure 7. Generally, developing a space-flight device requires identifying and addressing all the problems that might be encountered during its operation under the expected mission conditions. For the IPMC dust wiper, a series of issues and solutions were identified and are summarized in this section. The key issues include the critical need to protect the ionic constituents (i.e., avoid dehydration), reduce off-axis deformation, increase the actuation force, sustain the extreme temperature range and vacuum over a period of three years, and prevent electrolysis that causes the emission of hydrogen.



**FIGURE 5:** Graphic view of the EAP dust wiper on the MUSES-CN's mission and Nanorover (left) and a photograph of a prototype EAP dust wiper (right).



**FIGURE 6:** Combined schematic and photographic view of the EAP dust wiper.

The challenges and deficiencies that affect the material performance, controllability and robustness - identified as a result of this lesson learned - and the potential solutions are described in [Chapter 21 of Bar-Cohen, 2001 and 2004]. These deficiencies range from fundamental to repeatable fabrication issues and advancing IPMC to a mature technology would necessitate overcoming them. Unfortunately, the

current challenges are making IPMC unsuitable for the rigorous requirements of space flight hardware, particularly the mission constraints of operating on an asteroid. Future progress or alternative EAPs may provide a robust actuation capability that can be used effectively in such a planetary application.



**FIGURE 7:** A view of the dust wiper activated with high voltage to repel dust.

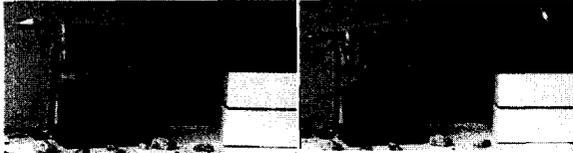
#### 4.2 Gripper and robotic arm lifter

By scrolling an electroded dielectric EAP film to a shape of a rope, an EAP actuator was constructed that becomes longer upon activation [Chapters 4 and 16 of Bar-Cohen, 2001 and 2004]. For this purpose, films with flat flexible electrodes on both surfaces were subjected to an electric field that squeezes the film by Maxwell forces, making it wider while maintaining the material volume. The produced actuator was used to lift and drop a graphite/epoxy rod serving as the equivalent of a robotic arm (see Figure 8).

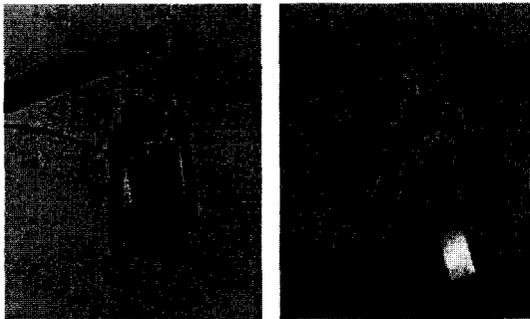
The planar configuration of such an EAP actuator with simple flat electrodes allows producing large lateral extension when electrically activated, and the strain is proportional to the square of the field. Forming electrodes with various patterns offers the potential capability to control the film deformation and possibly leads to contraction. The merit of this approach lies in the ability to manipulate and control the shape of the electric field. Unfortunately, after activating this actuator, the arm sustains a series of oscillations that need to be dampened to allow accurate positioning. This requires sensors and a feedback loop to support the kinematics of the system control. Several alternatives were explored, including establishment of a self-sensing capability, but more work is needed before such an arm can become practical.

To make the above arm as a robotic mechanism an end-effector in the form of a four finger gripper was developed (see Figure 9). The fingers were made of IPMC (Ionic polymer metal composite) strips with hooks at the bottom emulating fingernails.

As shown in Figure 9, this gripper grabs rocks very similar to the human hand.



**FIGURE 8:** A dielectric EAP actuator lifts/drops a miniature robotic arm with a four-finger gripper.



**FIGURE 9:** 4-finger EAP gripper lifting a rock.

### 5. Making robots actuated by EAP

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, great number of biologically inspired robots actuated by EAP materials emulating biological creatures is expected to emerge. The challenges to making such robots can be seen in Figure 10 where human-like and dog-like robots are shown to hop and express joy. Both tasks are easy for human and dogs to do but are extremely complex to incorporate into robots.

To promote the development of effective EAP actuators two platforms were developed (see Figure 11) that could impact future robotic applications of EAP. These platforms are available at the author's lab at JPL and they include an Android head that can make facial expressions and a robotic hand with activatable joints. Further, the robotic hand is equipped with tandems and sensors for the operation of the various joints mimicking human hand. The index finger of this hand is currently being driven 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 growing availability of EAP materials that exhibit high actuation displacements and forces is opening new avenues to bioengineering in terms of medical devices and assistance to humans in overcoming different forms of disability. Areas that

are being considered include an angioplasty steering mechanism, and rehabilitation robotics. For the latter, exoskeleton structures are being considered in support of rehabilitation or to augment the mobility and functionalities of patients with weak muscles.

**FIGURE 10:** A vision of joyfully hopping human-like and dog-like robots actuated by EAP materials (right).

**ACKNOWLEDGEMENT:** The human-like graphics was created by Robert M. Brown, JPL, where Zensheu Chang, JPL, was photographed hopping and smiling, whereas the eyes and nose of Jill Bonneville, JPL, were superimposed onto the face. The dog graphics is the contribution of David Hanson, U. of Texas, Dallas. This graphics was modified by Robert M. Brown, JPL.



The field of artificial muscles offers many important capabilities for the engineering of robots that are inspired by biological models and systems. The easy capability to produce EAP in various shapes and configurations can be exploited using such methods as stereolithography and ink-jet processing techniques. Potentially, a polymer can be dissolved in a volatile solvent and ejected drop-by-drop onto various substrates. Such rapid prototyping processing methods may lead to mass-produced robots in full 3D details including the actuators allowing rapid prototyping and quick transition from concept to full production [Chapter 14 at Bar-Cohen, 2001]. Biologically inspired robots may be developed with capabilities that are far superior to natural creatures since they are not constrained by evolution and survival needs. Examples may include artificial bugs that may walk on water, swim, hop, crawl and walk while reconfigure themselves as needed when required. Important addition to this capability can be the application of telepresence combined with virtual reality using haptic interfaces. While such capabilities are expected to significantly change future robots, additional effort is needed to develop robust and effective polymer-based actuators.



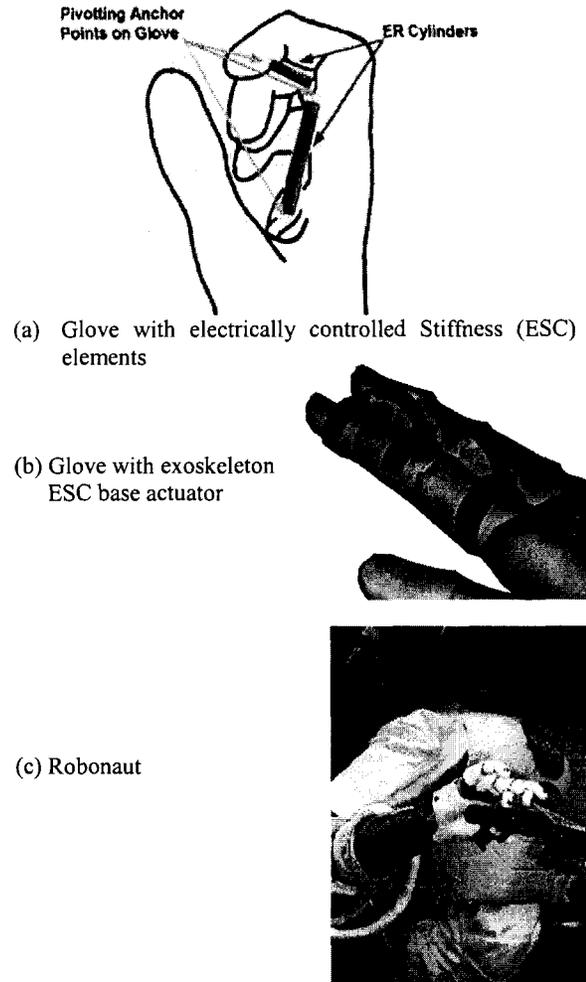
**FIGURE 11:** An android head and a robotic hand that are serving as biomimetic platforms for the development of artificial muscles

**ACKNOWLEDGEMENT:** This photo was made at JPL where the head was sculptured and instrumented by D. Hanson, University of Texas, Dallas. The hand was made by G. Whiteley, Sheffield Hallam U., UK.

## 6. Remote presence

Remotely operated robots and simulators that involve virtual reality and the ability to “feel” remote or virtual environment are highly attractive and offer unmatched capabilities [Chapter 4 in Bar-Cohen and Breazeal, 2003]. To address this need, the engineering community is developing haptic (tactile and force) feedback systems allowing users to immerse themselves in the display medium while being connected thru haptic and tactile interfaces to allow them to perform telepresence and “feel” at the level of their fingers and toes. Recently, the potential of making such a capability was enabled with the novel MEMICA system (MEchanical MIRRORing using Controlled stiffness and Actuators) concept [<http://ndea.jpl.nasa.gov/nasa-ndc/memica/memica.htm>]. For this purpose, scientist at JPL and Rutgers University used an EAP liquid, called Electro-Rheological Fluid (ERF), which becomes viscous under electro-activation. Taking advantage of this property, they designed miniature Electrically Controlled Stiffness (ECS) elements and actuators that are active on demand. Using this system stiffness and forces applied at remote or virtual environments are presented to the users via proportional changes in ERF viscosity. A detailed description of this haptic interface technology and the related system, MEMICA (MEchanical MIRRORing using Controlled stiffness and Actuators), is given in [Chapter 19 in Bar-Cohen 2001 and 2004]. Potential applications of this technology include training medical staff in executing surgical procedures using virtual reality. Also, it may allow operating as

remote presence by controlling such robots as the Robonaut (robotic astronaut) that was developed at the NASA Johnson Space Center. A schematic view of an ECS, its strategic placements on a glove and the Robonaut are shown in Figure 12.



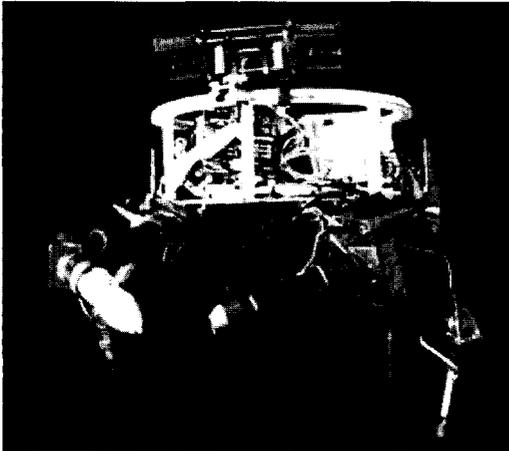
**FIGURE 12:** A schematic view of ECS elements that employ ERF making an operator “feel” the stiffness at a virtual or remote site. Such a system can potentially mirror the mechanical response of such robots as Robonaut [Provided through the courtesy of NASA Johnson Space Center, Huston, TX].

Using such the haptic capability of MEMICA can potentially benefit medical therapy in space and at distant human habitats. The probability that a medical urgent care procedure will need to be performed in space is expected to increase with the growth in duration and distance of manned missions. A major obstacle may arise as a result of the unavailability of on-board medical staff capable of handling every possible medical procedure that may be required. To conduct emergency treatments and

deal with unpredictable health problems the medical crews will need adequate tools and capability to practice the necessary procedure to minimize risk to the astronauts. With the aid of all-in-one-type surgical tools and a simulation system, astronauts with medical background would be able to practice the needed procedures and later physically perform the specific procedures. Medical staff in-space may be able to sharpen their professional skills by practicing existing and downloaded new procedures. Generally, such a capability can also serve people who live in rural and other remote sites with no readily available full medical care capability. As an education tool employing virtual reality, training paradigms can be changed while supporting the trend in medical schools towards replacing cadaveric specimens with computerized models of human anatomy.

### 7. Biologically inspired robots for planetary robotics

The evolution in the capabilities that are inspired by biology has increased to a level where more sophisticated and demanding fields, such as space science, are considering the use of such robots. At JPL, four and six legged robots are currently being developed for consideration in future missions to such planets as Mars. Such robots include the LEMUR (Limbed Excursion Mobile Utility Robot) as shown in Figure 13.



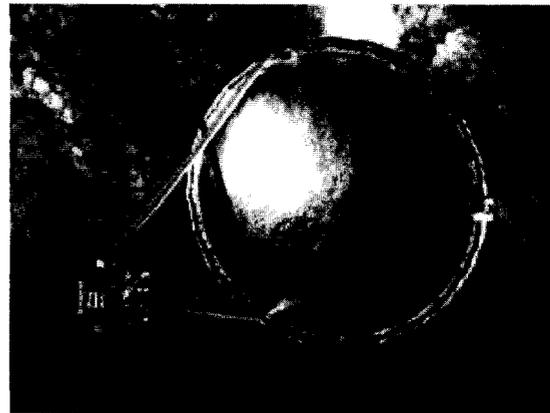
**FIGURE 13:** A new class of multi-limbed robots called LEMUR (Limbed Excursion Mobile Utility Robot) is under development at JPL [Courtesy of Brett Kennedy, JPL]

This type of robot would potentially perform mobility in complex terrains, perform sample acquisition and analysis, and many other functions

that are attributed to legged animals including grasping and object manipulation. This evolution may potentially lead to the use of life-like robots in future NASA missions that involve landing on various to planets. The details of such future missions will be designed as a plot, commonly used in entertainment shows rather than conventional mission plans of a rover moving in a terrain and performing simple autonomous tasks. Equipped with multi-functional tools and multiple cameras, the LEMUR robots are intended to inspect and maintain installations beyond humanity's easy reach in space. This spider looking robot has 6 legs, each of which has interchangeable end-effectors to perform the required mission. The axis-symmetric layout is a lot like a starfish or octopus, and it has a panning camera system that allows omni-directional movement and manipulation operations.

### 8. Deployable structures

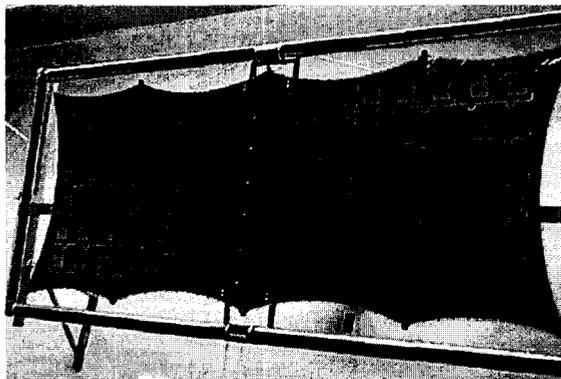
The use of polymers in space has evolved to the level that flight hardware structures made of such materials are increasingly part of NASA exploration missions. Some of the applications include the 1997 Mars Pathfinder mission use of a balloon to cushion the landing and the IN-STEP Inflatable Antenna Experiment (shown in Fig. 14), which flew on STS-76 on May 29, 1996 (concept developed by L'Garde, Inc.).



**FIGURE 14:** A Space Shuttle view of the L'Garde's Inflatable Antenna Experiment.

A rover with inflatable wheels was developed at JPL is another example. Generally, inflatable space structures can be produced to have very large surfaces that can be launched in a packed form and then inflated to shape and rigidize, creating large structures with a very low mass. An example of inflatable and rigidized synthetic aperture radar is shown in Figure 15. In order to obtain the maximum

benefit from such structures there is a need to precisely control their shape either prior to rigidization or in real time when periodic deformation and shape control are needed. EAP materials offer the potential of providing the necessary actuation technology for such structures. Such gossamer structures are expected to enable missions that are significantly beyond the capabilities of current technologies [Chapter 20 in Bar-Cohen, 2001 and 2004]. However, given the current limitations of the EAP technology, such capabilities can only be considered as a long-term goal.



**FIGURE 15:** Inflatable and rigidized synthetic aperture radar at the Jet Propulsion Laboratory.

## 9. Summary and outlook

For many years, electroactive polymers (EAP) received relatively little attention due to their limited actuation capability and the small number of available materials. In recent years, a series of new EAP materials have emerged that exhibit large displacement in response to electrical stimulation. This capability of the new materials is making EAP materials attractive as actuators for their operational similarity to biological muscles, particularly their resilience, damage tolerance, and ability to induce large actuation strains (stretching, contracting or bending). The application of these materials as actuators to drive various manipulation, mobility, and robotic devices involves multi-disciplines including materials, chemistry, electromechanics, computers, and electronics. Even though the force of actuation of existing EAP materials and their robustness require further improvement, there has already been a series of reported successes in the development of EAP-actuated mechanisms. Successful devices that have been reported include a fish-robot, audio speakers, catheter-steering element, miniature manipulator and miniature gripper, active diaphragm, and dust wiper. The field of EAP has enormous potential in many application areas, and, judging from the range of

inquiries that the author has received in the last five years, it seems that almost any aspect of our lives can be impacted. Some of the considered applications are still far from being practical, and it is important to tailor the requirements to the level that current materials can address. Using EAP to replace existing actuators may be a difficult challenge and therefore it is highly desirable to identify a niche application where EAP materials would not need to compete with existing technologies.

Some of the challenges that are facing the users of EAP materials and could help expand their potential applications to space applications include the availability of EAP materials with low glass transition temperature and significant response at low or high temperatures. Space applications are of great need for materials that can operate down to single digit degrees of Kelvin or high temperatures in the hundreds of Celsius as on Venus. Another challenge to EAP is the development of large scale EAP in the form of films, fibers and others. The required dimensions can be as large as several meters or kilometers and in such dimensions they can benefit space applications allowing development of such large gossamer structures as antennas, solar sails, optical components and others in support of future NASA missions.

This field is far from mature and progress is expected to change the field in future years. As the technology evolves the days are nearing when the first armwrestling match between a robot that is actuated by EAP and human will be held. A robot win will make it clear that EAP performance has reached a level at which devices designed to emulate many of the physical functions that a human can perform are altogether possible. Making such capability will allow NASA to conduct missions that simulate human operation in other planets ahead of a landing of human.

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