# ELECTROACTIVE POLYMERS AS ARTIFICIAL MUSCLES - CAPABILITIES, POTENTIALS AND CHALLENGES

**Yoseph Bar-Cohen**
JPL/Caltech, (MC 82-105), 4800 Oak Grove Drive, Pasadena, CA 91109-8099
Phone 818-354-2610, Fax 818-393-4057, yosi@jpl.nasa.gov, web: http://ndea.jpl.nasa.gov

## ABSTRACT

For many years, electroactive polymers (EAP) received relatively little attention due to the small number of available materials and their limited actuation capability. The recent emergence of EAP materials with large displacement response changed the paradigm of these materials and their potential capability. The main attractive characteristic of EAP is their operational similarity to biological muscles, particularly their resilience and ability to induce large actuation strains. Unique robotic components and miniature devices are being explored, where EAP serve as actuators to enable new capabilities. In recognition of the need for international cooperation among the developers, users and potential sponsors, an SPIE Conference was organized for the first time on March 1-2, 1999, in Newport Beach, California. The conference was the largest ever on EAP, and it marked an important milestone, turning the spotlight onto these emerging materials and their potential. Following this success, an MRS conference was initiated to address the fundamental issues related to the material science of EAP. The WW-EAP newsletter was initiated to bring the worldwide EAP community even closer. A homepage was also created to link worldwide EAP research and development facilities websites. In this paper, the current capabilities and potentials as well as the challenges of state-of-the art EAP will be reviewed.

## INTRODUCTION

Polymers are increasingly being chosen for aerospace mechanisms for their low density. Initially, these materials were used to produce components and structures but in recent years other characteristics of polymers have become attractive including their resilience. A balloon was used to cushion the deployment of the Mars Pathfinder lander on July 4, 1997, paving the way for the recent large number of initiatives in the area of inflatable structures. Such applications have emerged in the form of rover (Figure 1), Aerobot, inflatable telescopes (Figure 2), radar antennas, and others. Some of these applications have reached flight experiment, whereas others are now at advanced stages of development. Polymers were also reported to be used as actuators including (a) McKibben muscle actuators [Schulte, 1961] – These are air tubes with an angularly breaded fiber reinforcement that contract significantly when inflated, delivering a large force at low frequency. Such actuators are being considered for potential robotic applications and several demonstration units have been reported; (b) Shape memory polymers – These materials sustain a volume change of over 40 times using pressure and heat to stow it in a compact form, whereas a temperature of 55°C causes a recovery of the pre-pressed shape [Sokolowski, et al, 1999]; (c) Electrorhological fluids – These are electroactive polymer liquids that sustain an increase in viscosity under electrical field stimulation. They are used in electrically controlled-hydraulic mechanisms.

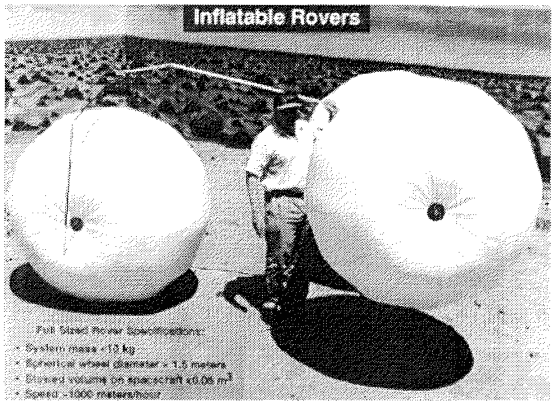



**FIGURE 1**: JPL rover using inflatable wheels (J. Jones, the Task Manager, is shown in the photo).

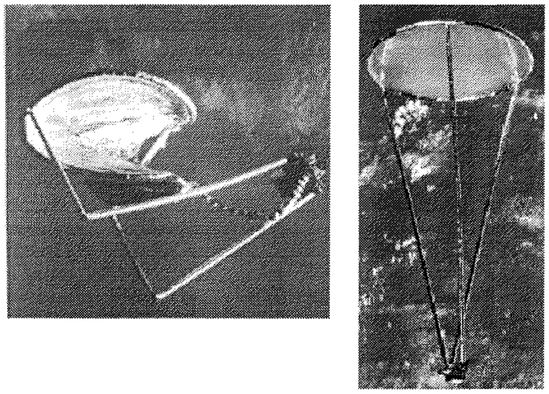


**FIGURE 2**: A Space Shuttle view of an inflatable structure experiment (May 1996). Left – During inflation and Right – Fully open.

The use of polymers with electroactive reaction has emerged only in this decade with the introduction of EAP materials having significant displacement levels. These materials are highly attractive for their low-density materials with large strain capability that can be as high as two orders of magnitude greater than the striction-limited, rigid and fragile electroactive ceramics (EAC). Also, these materials are superior to shape memory alloys (SMA) in their spectral response, lower density, and resilience. However, these 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 EAPs is their ability to emulate biological muscles with high toughness, large actuation strain and inherent vibration damping. This similarity 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 would be feasible with any other conventional actuation mechanisms. Unfortunately, the force actuation and mechanical energy density of EAPs are relatively low, limiting the potential applications that can be considered at the present time. To overcome this limitation there is a need for development in numerous multidisciplinary areas from computational chemistry, comprehensive material science, electromechanic analysis and 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.

In recognition of the need for international cooperation among the developers, users and potential sponsors, an SPIE Conference was organized for the first time in March 1999. This conference that was the largest ever on EAP marking an important milestone. Following this success, an MRS conference was initiated to address fundamental issues related to the material science of EAP. As of 1999, the science and engineering community is offered two annual international conferences (SPIE and MRS) that are solely dedicated to the subject of EAP. The WW-EAP Newsletter was initiated (http://eis.jpl.nasa.gov/ndeaa/nasa-nde/newsltr/WW-EAP_Newsletter.PDF) and a homepage was formed linking worldwide EAP research and development websites (http://ndeaa.jpl.nasa.gov/nasa-nde/lommas/eap/EAP-web.htm). Also, government resources are being devoted at unprecedented levels to sponsor research in this area. The increased research and the improved collaboration among the developers, users and sponsors are expected to foster to progress at a significantly high rate.

The author challenged the EAP community to develop robotic arms actuated by artificial muscles that would win an arm wrestling match with a human (Figure 3). Progress towards this goal will lead to great benefits, particularly in the medical area, including effective prosthetics. Decades from now, EAP may be used to replace damaged human muscles, leading to a "bionic human." A remarkable contribution of the EAP field would be to one day seeing a handicapped person jogging to the grocery store using this technology.

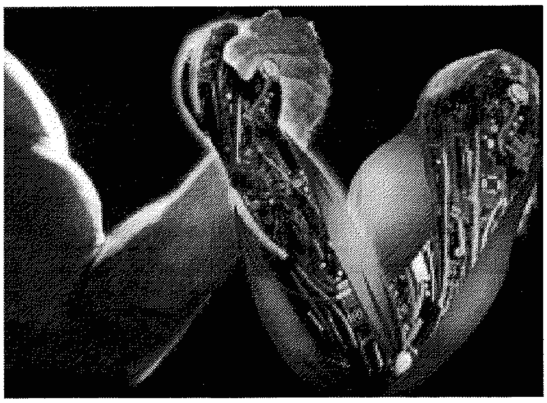


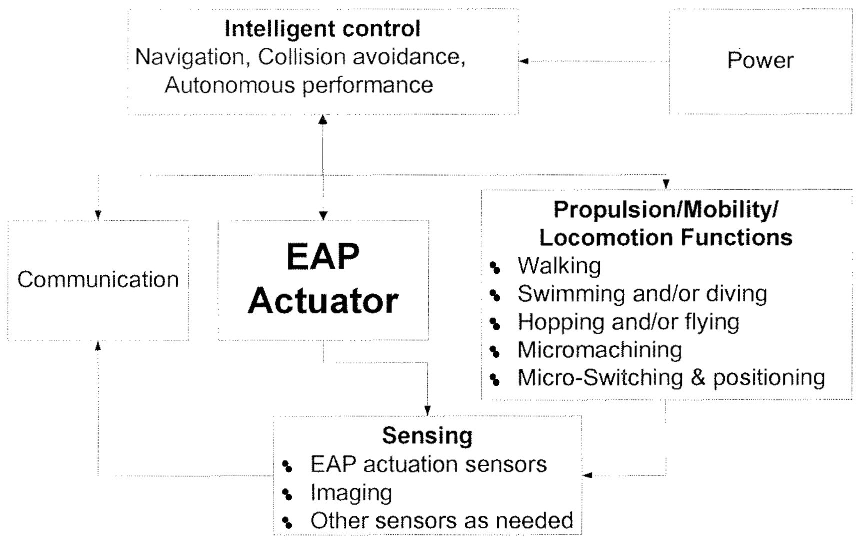
**FIGURE 3**: Grand Challenge for the EAP Community.

## NEED FOR AN ESTABLISHED EAP INFRASTRUCTURE

The field of EAP is relative new, and it is highly attractive due to the materials' capability to induce strong displacements and emulate biological muscles. A system that is driven by EAP materials can consist of components that are shown in the block diagram of Figure 4. While each of the listed components is at various research phases, the field of EAP actuators is the least advanced and requires extensive efforts as discussed in this paper.

Unfortunately, the materials that have emerged so far are still exhibiting low force and/or very slow response, and are far from being effective. Moreover, there are no commercially available robust EAP materials that can be considered for application in practical devices. In recent years, a series of EAP materials that induce large displacements were documented, including ion exchange membranes, gel polymers, perfluorinated sulfonic polymers, self-assembled mono-layered polymers, electrostrictives, electrostatics and piezoelectrics [Bar-Cohen, 1999a]. In order to be able to transition these materials from a development phase to effective actuators there is a need to establish the required "infrastructure". The author's view of this infrastructure and the areas needing simultaneous development of effective materials, processes and applications are shown schematically in Figure 5. There is a need for an adequate understanding of EAP materials' behavior and the requirements necessary to assure their durability under various service conditions. Further, enhancing their actuation force will require the development of models that employ computational chemistry, comprehensive material science, electro-mechanic analytical tools and improved materials processes. Efforts are needed 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 will need to be refined to maximize their actuation capability and robustness. Various configurations of EAP actuators, sensors and potential MEMS will need to be studied and modeled to produce an arsenal of effective actuators. The development of the infrastructure is multidisciplinary and requires international collaboration.

**FIGURE 4**: A schematic diagram of the basic components of an EAP-driven system.




## BIOLOGICAL MUSCLES AND SCIENCE FICTION

In developing effective EAP materials, the characteristics of biological muscles can serve as a baseline. Generally, the performance characteristics of muscles are difficult to measure. Documented measurements were made on the large shell-closing muscles of scallops. The data shows a peak stress level of 150-300 KPa developed at a strain of about 25%. The maximum power output is 150-225 W/kg, whereas the average power is about 50 W/kg with an energy density of 20-70 J/kg, decreasing with an increase in speed. The time scale for contraction is about 0.1-1 second. Since muscle is fundamental to animal life and changes little between species, we can regard it as a highly optimized system. It is also a surprisingly complex system depending on chemically-driven reversible hydrogen bonding between two polymers, actin and myosin. In recognition of human muscle as a baseline, there is a need for cooperation between the EAP materials and the biomedical community specializing in biological muscles. Once effective EAP materials can be made, biologically inspired robots and locomotives can be made and walking, flying, hoping digging, swimming and diving robots would become feasible. This initiative is compatible with the recent NASA goal to develop robotic colonies.

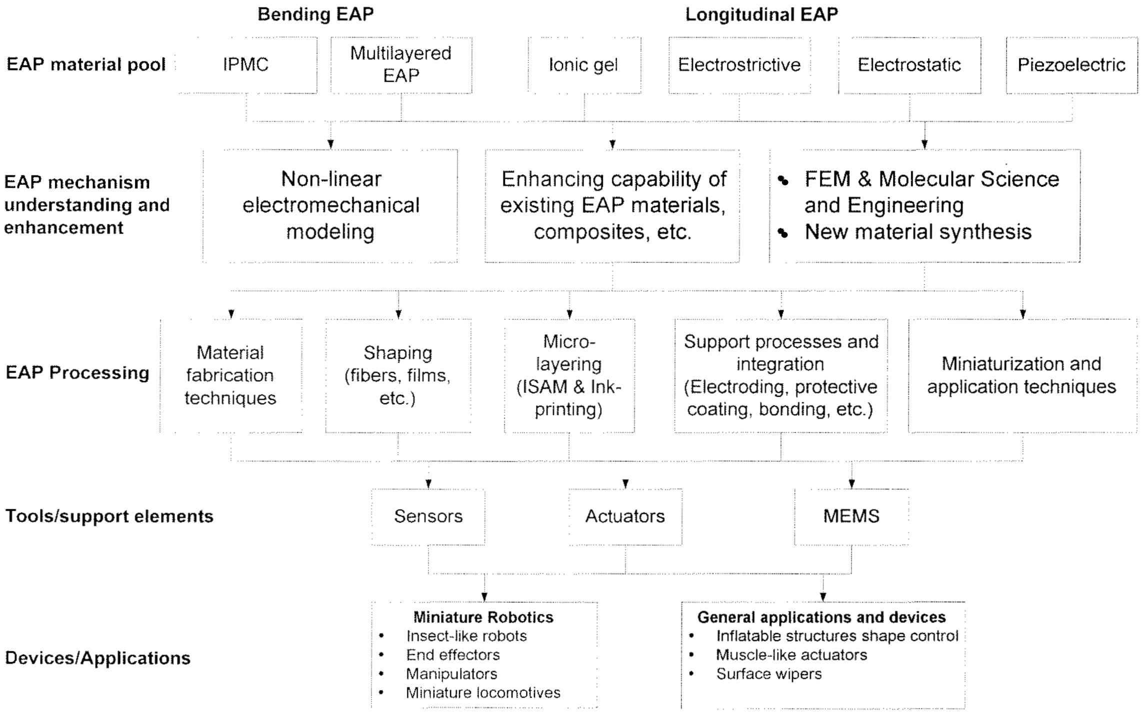



**FIGURE 5**: EAP infrastructure and areas needing attention.

Insects mobility is under extensive study and there is a relatively large body of knowledge in place, as for example at the University of California, Berkeley [Full and Tu, 1990]. A windmill was used with a photoelastic coating (Figure 6) to study the detailed insects walking mechanisms, where insects with various numbers of legs were investigated. Also, the size of electronic devices has become so small that insects can be instrumented to perform tasks once viewed as science fiction. At the University of Tokyo, Japan, A spider and other insects were instrumented as a locomotive to carry a backpack of wireless electronics (Figure 7). Actuation technology developments are expected to enable insect-like robots (Robosects) that can be launched into structures hidden areas (e.g., aircraft engine) to perform inspection and maintenance tasks.

Low-cost missions that have high science pay-off with attention-grabbing technological achievements are very attractive to the public. Mars Pathfinder was an excellent example of the success of such an approach where a low-cost exploration mission was executed with a plot consisting of a series of impressive activities. JPL is planning to reach a growing number of planets and small bodies inside and outside of our solar system with increased challenges to conduct in-situ science over large areas of these planets at increasingly constrained costs and greater complexities. A mix of innovative science and technology with imaginative tasks that are approaching science fiction levels would offer NASA exciting future missions. In future years, EAP may emulate the capabilities of terrestrial creatures with integrated multidisciplinary capabilities to launch missions with innovative plots. Some biological functions that can be adapted include soft-landing like cats, traversing distances by hopping like a grasshopper and digging and operating cooperatively as ants (Figure 8).

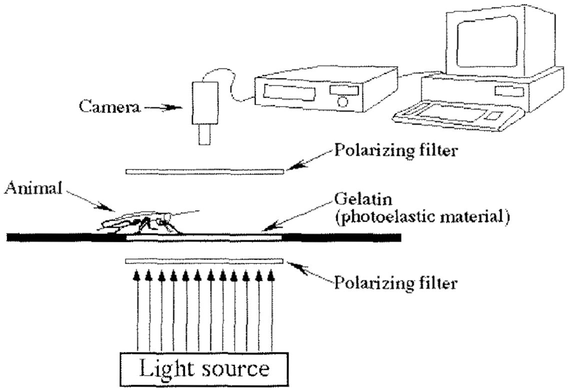



**FIGURE 6**: A Schematic view of the UC Berkeley's test system for insect walking http://rjf2.biol.berkeley.edu/Full_Lab/FL_Publications/PB_Posters/94ASZ_Turning/94ASZ_Turning.html

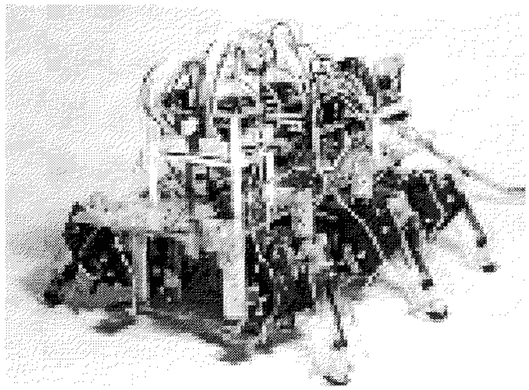


**FIGURE 7**: An instrumented spider at the University of Tokyo illustrates the potential to NDE in terms of mobile sensors [http://www.leopard.t.u-tokyo.ac.jp/].

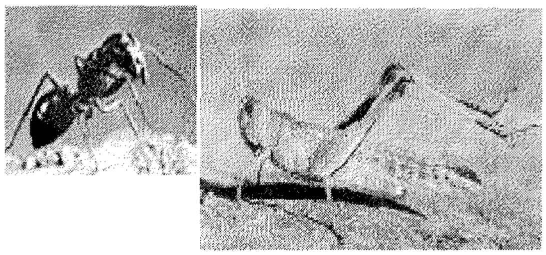


**FIGURE 8**: Robosect colonies that emulate insect capabilities and behavior offer exciting future NASA missions.

As a scenario for futuristic missions - multiple Robosects can be designed to search for evidence of former/existing life, resources, rare minerals and the presence of water, determine magnetic and other forces, reach crevices, construct miniature fixtures, examine the geophysics, carry relays for remote communication as well as perform unique experiments. Sensing options such as smelling and tasting, using chemical sensors equivalent biological ones, can be considered. Robosects can be equipped with various practical locomotion techniques, such as hopping and flying to traverse large distances, crawling to reach specific locations, as well as digging tunnels for underground operations. At low gravity and low ambient pressures, particularly on small bodies, hopping offers an effective form of traversing long distances. On wet planets and moons, such as Europa, swimming and diving options can be added. The development of a cooperative colony will offer redundancy allowing for the execution of tasks that are significantly beyond the capability of individual Robosects. Moreover, the option of "maintenance/emergency crews" can be explored. Ant colonies are an excellent model for cooperative Robosects and it is not unusual to see a group of ants carrying a large leaf, which is considerably larger and heavier than they are individually. Moreover, Robosects can be designed to perform self-cleaning for dust removal from their solar cells to avoid losing the power-generating capability as can be encountered on Mars. The possibility of self-cloning can also be explored.

## DEVELOPMENT OF EAP UNDER JPL LEAD

Under the author's lead, planetary applications using EAP are being explored while improving the understanding, practicality and robustness of these materials. EAP materials are sought as a substitution to conventional actuation components such as motors, gears, bearings, screws, etc. This research and development effort has been conducted since 1995 under the NASA task of so-called Low Mass Muscle Actuator (LoMMAs), and the current team consists of JPL, NASA-LaRC, VT, Rutgers University, and ESLI having cooperative efforts with Osaka National Research Institute, Japan, and, Kobe University, Japan [Bar-Cohen, et al, 1999c].

Under the NASA task, longitudinal and bending EAP are being investigated for planetary applications, and a dust-wiper, gripper and robotic arm were demonstrated [Bar-Cohen, et al, 1999b]. The dust-wiper (Figure 9) is currently being developed for the Nanorover's optical/IR window, which is part of the MUSES-CN mission. The MUSES-CN is a joint NASA and Japanese Space Agency mission scheduled for launch in January 2002, from Kagoshima, Japan, to explore the surface of a small near-Earth asteroid. The team is testing the use of highly effective ion-exchange membrane metallic composites (IPMC) made of perfluorocarboxylate-gold composite with two types of cations, tetra-n-butylammonium and lithium. Under a potential difference of less than 3-V, these IPMC materials are capable of bending beyond a complete loop. A unique ~100-mg blade with fiberglass brush was developed by ESLI (San Diego, CA) and subjected to a high voltage to repel dust, augmenting the brushing mechanism provided by the blade.

Generally, space applications are the most demanding in terms of operating conditions, robustness and durability. The team is jointly addressing the associated challenges. Several issues that are critical to the operation of IPMC are examined, including its response in vacuum and low temperatures, as well as the effect of the material's electromechanical characteristics on its actuation capability. The use of highly effective IPMC materials, mechanical modeling, unique components and a protective coating are increasing the probability of success for the EAP-actuated dust-wiper. Another application of EAP actuators is the development of a miniature robotic arm with closed-loop control (Figure 10). A longitudinal EAP, based on SRI international developed actuator, is used to lift and drop the arm, whereas a 4-finger gripper is used to grab rocks and other objects. The EAP fingers operate much like a human hand when grabbing the rock as shown in Figure 11.

Generally, the practical application of EAP materials is still a great challenge. No effective and robust EAP material is currently available commercially. Further, there is no established database that documents the properties of the existing EAP materials.

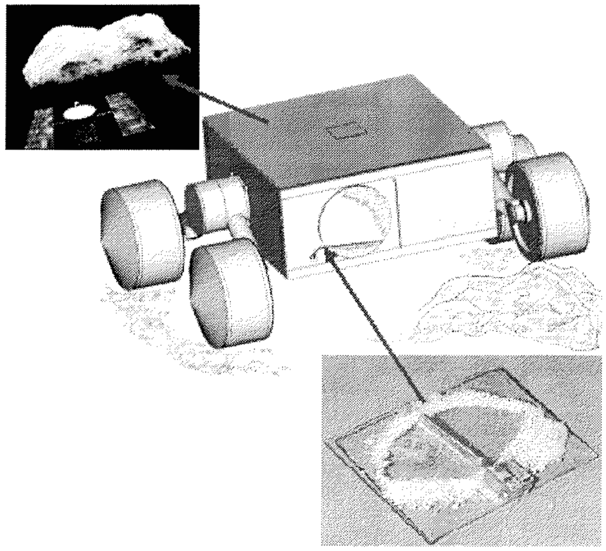


**FIGURE 9:** Schematic view of the EAP dust-wiper on the MUSES-CN's Nanorover (right) and a photograph of a prototype EAP dust-wiper (left).

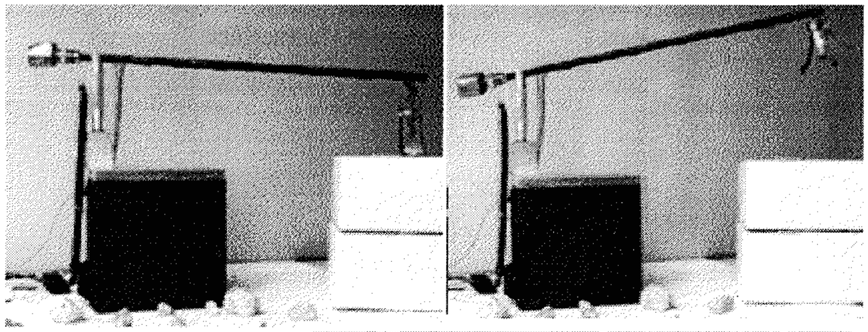


**FIGURE 10**: A miniature robotic arm using EAP actuators to provide the lifting/dropping of the arm and manipulate the gripper fingers.

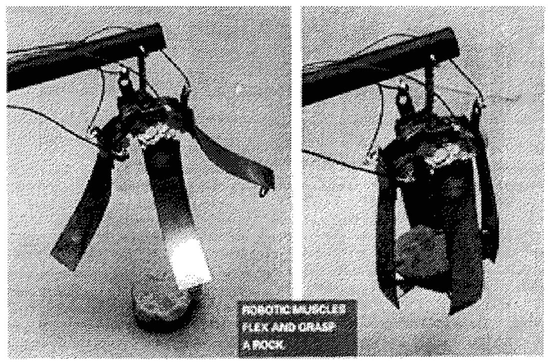



**FIGURE 11**: 4-finger EAP gripper lifting a rock much like a human hand (Discover, Vol. 19 No. 8 (August 1998), p. 33)

## CONCLUDING REMARKS

Electroactive polymers have emerged in recent years with great potential to enabling unique mechanisms that can emulate biological systems. Much more research and development work still needs to be done before EAP will become the actuators of choice. The development of an effective infrastructure for this field is critical to the commercial availability of robust actuation materials for practical applications. The challenges are enormous, but the recent international trend towards more cooperation and greater visibility to the field as well as the surge in funding and research offer great hope for the future of these exciting materials. Science fiction tasks will be transitioned to reality at an unprecedented rate once effective EAP materials become available.

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