

# Biologically Inspired Robots as Artificial Inspectors

Yoseph Bar-Cohen

Jet Propulsion Laboratory/Caltech

4800 Oak Grove Drive, M/S 82-105, Pasadena, CA 91109, USA

e-mail: [yosi@jpl.nasa.gov](mailto:yosi@jpl.nasa.gov) Web: <http://ndeaa.jpl.nasa.gov>

## ABSTRACT

Imagine an inspector conducting NDE on an aircraft where you notice something weird about him – he is not real but rather he is a robot. Your first reaction would probably be to say “it’s unbelievable but he looks real” just as you would react to an artificial flower that is a good imitation. This science fiction scenario could become a reality at the trend in the development of biologically inspired technologies, and terms like artificial intelligence, artificial muscles, artificial vision and numerous others are increasingly becoming common engineering tools. For many years, the trend has been to automate processes in order to increase the efficiency of performing redundant tasks where various systems have been developed to deal with specific production line requirements. Realizing that some parts are too complex to handle with a simple automatic system robotic mechanisms were developed to manipulate parts and to perform complex and delicate tasks. Aircraft inspection has benefited from this evolving technology where manipulators and crawlers are developed for rapid and reliable inspection. One of the limiting factors that hampered the wide use of robotics for inspection of aircraft and other complex structures is the economical aspect of handling small quantities of complex parts. Autonomous robots, which may look like human, can potentially address the need to inspect structures with configuration that are not predetermined. The operation of these robots may take place at harsh or hazardous environments that are too dangerous for human presence. Making such robots is becoming increasingly feasible and in this paper the state of the art will be reviewed.

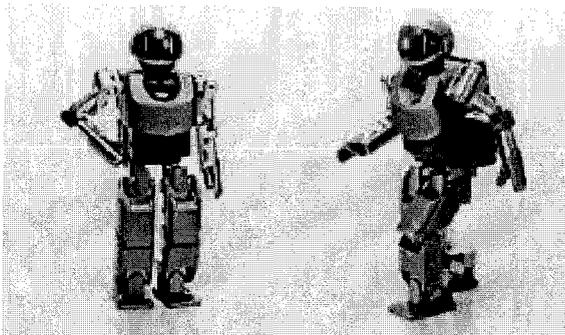
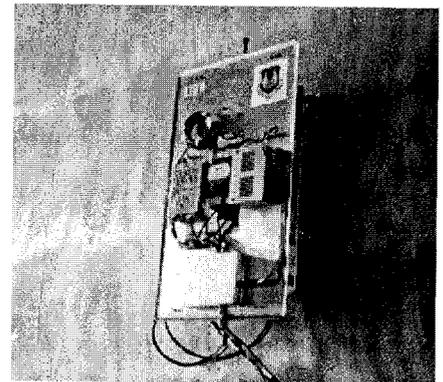
## INTRODUCTION

The field of NDE is increasingly benefited from advancement in robotics and automation [Bar-Cohen, 2000a]. Crawlers and various manipulation devices are commonly used to perform variety of inspection tasks from C-scan to contour following and other complex functions. At JPL a multifunctional automated crawling system (MACS), shown in Figure 1, was developed to simplify scanning in field conditions where a novel mobility platform was developed for integration of NDE instruments for using in scanning tasks. Enhancement of the inspection capability and allowing access to difficult to reach areas required capabilities that in today technology can be performed only human operator. Making a robot to behave and operate like human is a challenge that seems to be a science fiction but with the current trend may not be a distant reality.

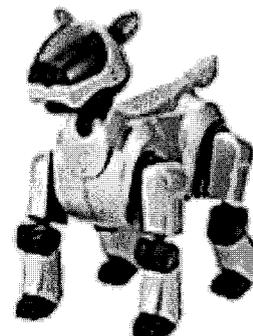
Creating robots that mimic the shape and performance of biological creatures, i.e. biomimicking, has always been a highly desirable engineering objective. Searching the internet under the keyword robots would identify many links to research and development projects that are involved with the development of robots with features that are biologically inspired. The entertainment and toy industries were greatly benefited of the advancement in this technology. Increasingly robots are used in movies showing creatures with realistic behavior even if they don’t exist anymore as in the case of dinosaurs in the movie “Jurassic Park”. Visiting toy stores

one can easily see how far the technology progressed in making inexpensive toys that imitate biology – such store displays include frogs swimming in a fish bowl and dogs walking back and forth and possibly even barking. Operating robots that emulate the functions and performance of human or animal involve using capabilities of actuators and mechanisms that depend on the state-of-the-art. Upper-end robots and toys are becoming increasingly sophisticated allowing them to walk and talk with some that can be operated autonomously and can be remotely reprogrammed to change their characteristic behavior (see Figure 2 and 3). Some of the toys or robots can even make expressions and exhibit behavior that is similar to human and animals. An example of such a robot is shown in Figure 4 where the robot Donna reacts to human expressions including smiling. As this technology evolves it is becoming more likely to believe that in the future human like robots may be developed to operate as artificial NDE inspectors and perform tasks that are highly reliability and very repeatable without human faults of making errors, needing a break, being distracted or getting tired.

**FIGURE 1:** MACS crawling on the C-5 aircraft [Bar -Cohen, 2000a].

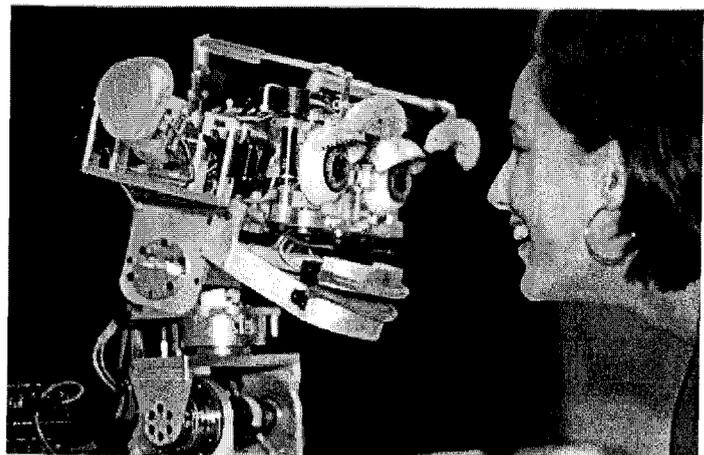


**FIGURE 2:** Sony's SDR3 is an example of a robot that can perform functions that emulate human [<http://www.designboom.com/eng/education/robot.html>]



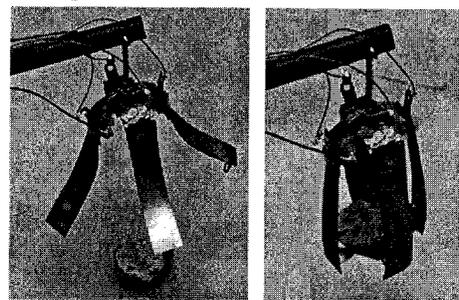
**FIGURE 3:** Sony's AIBO - Sony 2nd Generation ERS-210 is a sophisticated pet-like robot [[http://www.us.aibo.com/ers\\_210/product.php?cat=aibo](http://www.us.aibo.com/ers_210/product.php?cat=aibo)]

**FIGURE 4:** The robot, Donna, responds to human expressions [courtesy of Cynthia Breazeal, MIT, <http://www.ai.mit.edu/people/cynthia/cynthia.html>]



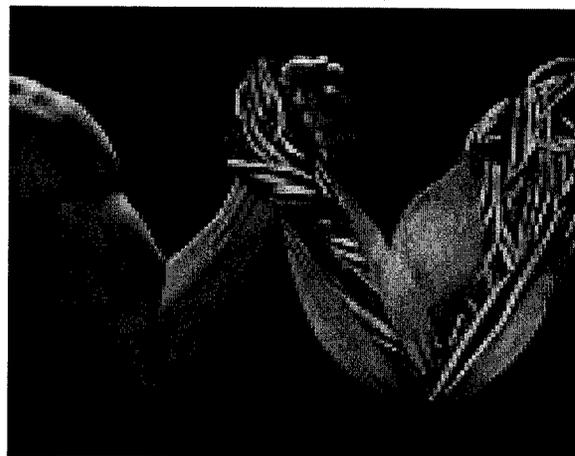
In spite of the success in making robots that mimic biology there is still a large gap between the performance of robots and nature creatures. The required technology is multidisciplinary and has many aspects and one of them is the need for actuators that emulate muscles. The potential for such actuators is increasingly becoming feasible with the emergence of effective electroactive polymers (EAP) [Bar-Cohen, 2001a]. These materials have functional similarities to biological muscles, including resilience, damage tolerance, and large actuation strains (stretching, contracting or bending), earning them the moniker Artificial Muscle. 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 to high costs, weight and premature failures. Visco-elastic EAP materials can potentially provide more lifelike 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.

The capability of EAPs to emulate muscles offers robotic capabilities that have been in the realm of science fiction when relying on existing actuators. The large displacement that can be obtained using low mass, low power and, in some of the EAPs, also low voltage, makes them attractive actuators. As an example of an application, at JPL EAP actuators that can induce bending and longitudinal strains were used to design and construct a miniature robotic arm (see Figure 5). This robotic arm illustrates some of the unique capability of EAP, where its gripper consisted of four bending type EAP finger strips with hooks at the bottom emulating fingernails and it was made to grab rock similar to human hand.



**FIGURE 5:** 4-finger EAP gripper lifting a rock.

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 SPIE International 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 and turning the spotlight onto these emerging materials and their potential. This SPIE conference is now organized annually and has been steadily growing in number of presentations and attendees. Currently, there is a website 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>], and a semi-annual Newsletter is issued electronically [<http://ndeaa.jpl.nasa.gov/nasa-nde/lommas/eap/WW-EAP-Newsletter.html>]. Also, in March 2001, a book that covers this field was issued by SPIE Press [<http://ndeaa.jpl.nasa.gov/nasa-nde/yosi/yosi-books.htm>]



**FIGURE 6:** Grand challenge for the development of EAP actuated robotics.

The increased resources, the growing

number of investigators conducting research related to EAP, and the improved collaboration among developers, users, and sponsors are expected to lead to rapid progress in the coming years. In 1999, the author posed a challenge to the worldwide research and engineering community to develop a robotic arm that is actuated by artificial muscles to win an arm wrestling match against a human opponent (Figure 6). Progress towards this goal will lead to significant benefits, particularly in the medical area, including effective prosthetics. Decades from now, EAP may be used to replace damaged human muscles, potentially leading to a "bionic human." A remarkable contribution of the EAP field would be to one day see a handicapped person jogging to the grocery store using this technology.

### **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, 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]. 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, 2001a].

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 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 ten years where effective materials that can induce over 300% strains have emerged [Kornbluh and Pelrine, 2001].

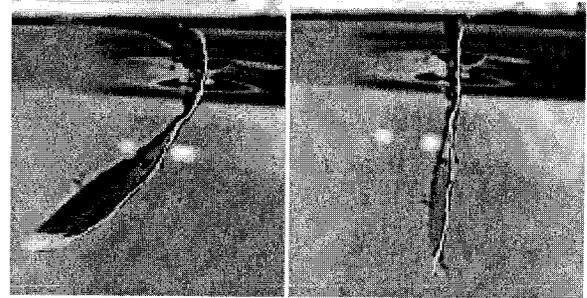
EAP can be divided into two major categories based on their activation mechanism including ionic and electronic (Table 1). The electronic EAP, such as electrostrictive, electrostatic, piezoelectric, and ferroelectric, are driven by Coulomb forces. This type of EAP materials can be made to hold the induced 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 ( $>100\text{-V}/\mu\text{m}$ ) 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).

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

<b>Electronic EAP</b>	<b>Ionic EAP</b>
Dielectric EAP	<ul style="list-style-type: none"> <li>• Carbon Nanotubes (CNT)</li> </ul>
Electrostrictive Graft Elastomers	<ul style="list-style-type: none"> <li>• Conductive Polymers (CP) (see Figure 7)</li> </ul>
Electrostrictive Paper	<ul style="list-style-type: none"> <li>• ElectroRheological Fluids (ERF)</li> </ul>
Electro-Viscoelastic Elastomers	<ul style="list-style-type: none"> <li>• Ionic Polymer Gels (IPG)</li> </ul>
Ferroelectric Polymers	<ul style="list-style-type: none"> <li>• Ionic Polymer Metallic Composite (IPMC)</li> </ul>
Liquid Crystal Elastomers (LCE)	

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 7). 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. The address of this website is <http://ndeaa.jpl.nasa.gov/nasa-nde/lommas/eap/EAP-recipe.htm>

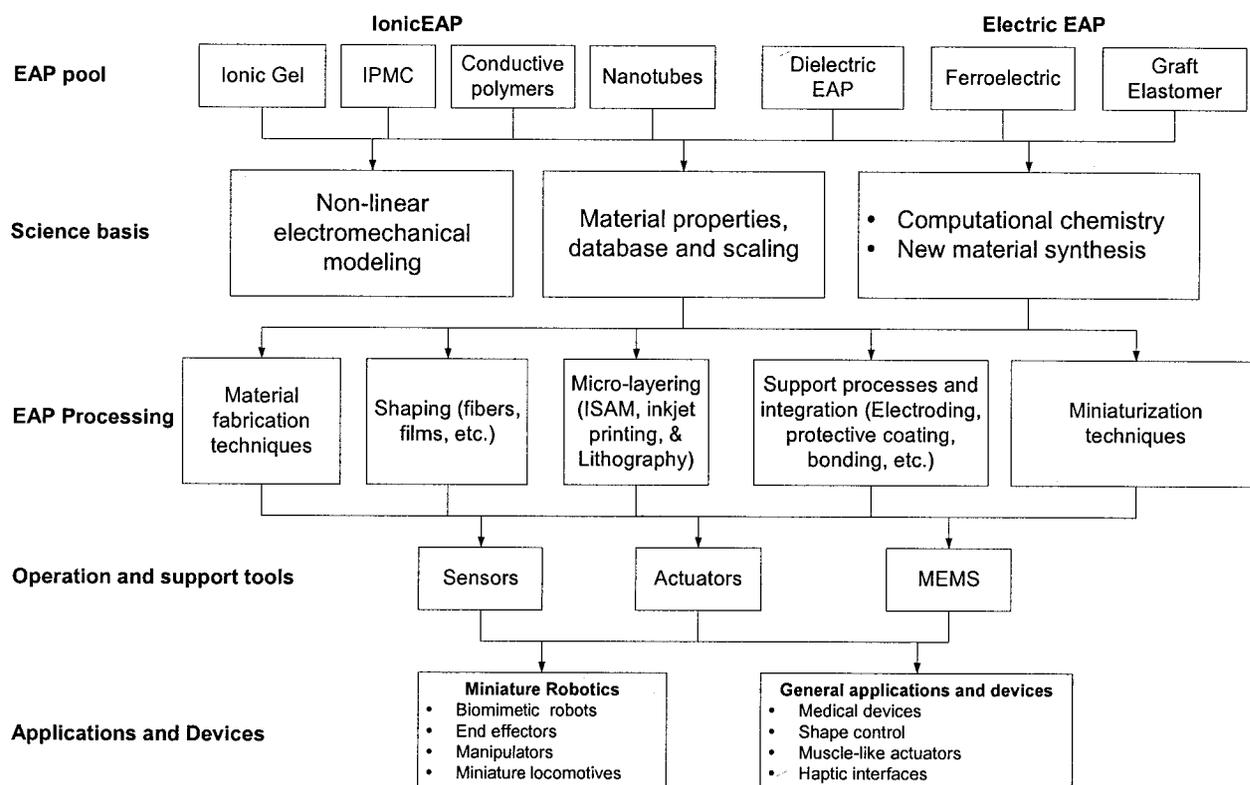


**FIGURE 7:** Conductive EAP actuator is shown bending under stimulation of 2-V, 50-A.

### **NEED FOR EAP TECHNOLOGY INFRASTRUCTURE**

As polymers, EAP materials 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 toughness, 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 to establish an adequate EAP infrastructure (Figure 8). Effectively addressing the requirements of the EAP infrastructure involves developing adequate understanding of EAP materials' behavior, as well as processing and characterization techniques.

Enhancement of the actuation force requires understanding the basic principles using computational chemistry models, comprehensive material science, electro-mechanics analytical tools and improved material processing techniques. 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 the EAP materials actuation capability and robustness. Methods of reliably characterizing the response of these materials are required to establish database with documented material properties in order to support design engineers considering use of these materials and towards making EAP as actuators of choice. Various configurations of EAP actuators and sensors will need to be studied and modeled to produce an arsenal of effective smart EAP driven system. In the last three years, significant international effort has been made to address the various aspects of the EAP infrastructure and to tackle the multidisciplinary issues [Bar-Cohen, 2001a]. In recent years, numerous researchers and engineers have addressed each element of the block diagram shown in Figure 8 as can be seen from the conference proceedings of the SPIE and MRS conferences on this subject [Bar-Cohen, 1999, 2000 and 2001b]. 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 product will emerge in spite of the current limitations of EAP materials.



**FIGURE 8: EAP infrastructure block diagram**

### 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. Such robots can be programmed to take on such tasks as performing NDE procedures. The challenges to making such a robot are portrayed in Figure 9 where the robot shown to hop and express joy. Both tasks are easy for human to do but are extremely complex to incorporate into a robot.

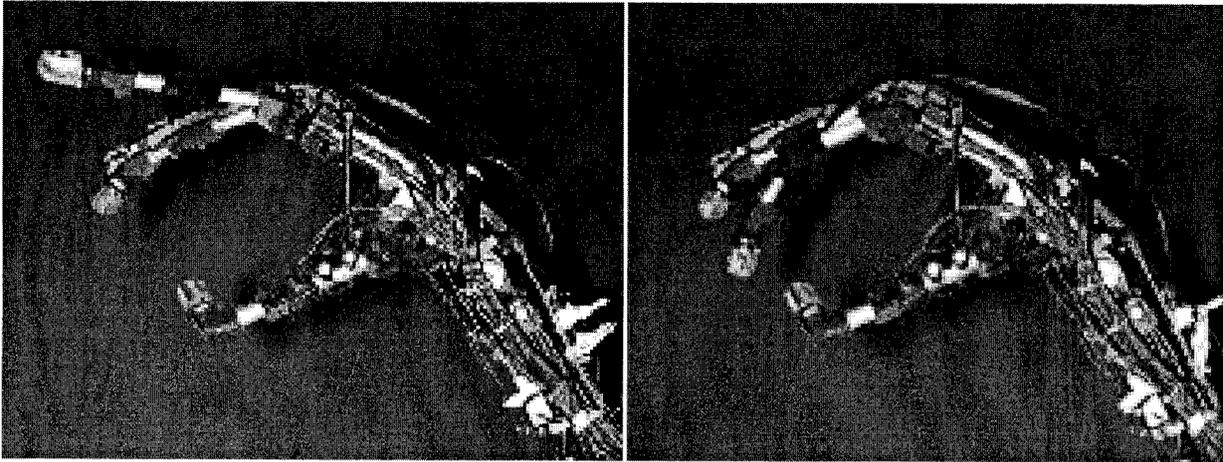
To promote the development of effective EAP actuators, which could impact future robotics, toys and animatronics, two platforms were developed. These platforms include an Android head [Figure 10, and video on <http://ndcaa.jpl.nasa.gov/nasa-nde/lommas/eap/EAP-web.htm>] that can make facial expressions and a robotic hand with activatable joints. At present, conventional electric motors are producing the required deformations to make relevant facial expressions of the Android. Data is acquired, stored in a personal computer, and analyzed through a dedicated neural network. Human expressions can be acquired by a digital camcorder in the form of motion capture sequences and can be imitated by 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. Further, the robotic hand [Figure 11, and video on <http://ndcaa.jpl.nasa.gov/nasa-nde/lommas/eap/EAP-web.htm>] is equipped with tendons 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.



**FIGURE 9:** Biomimetic robot



**FIGURE 10:** An android head (Photographed at JPL) as EAP platform will use such actuators to make facial expressions (Courtesy of G. Pioggia, University of Pisa, Italy).

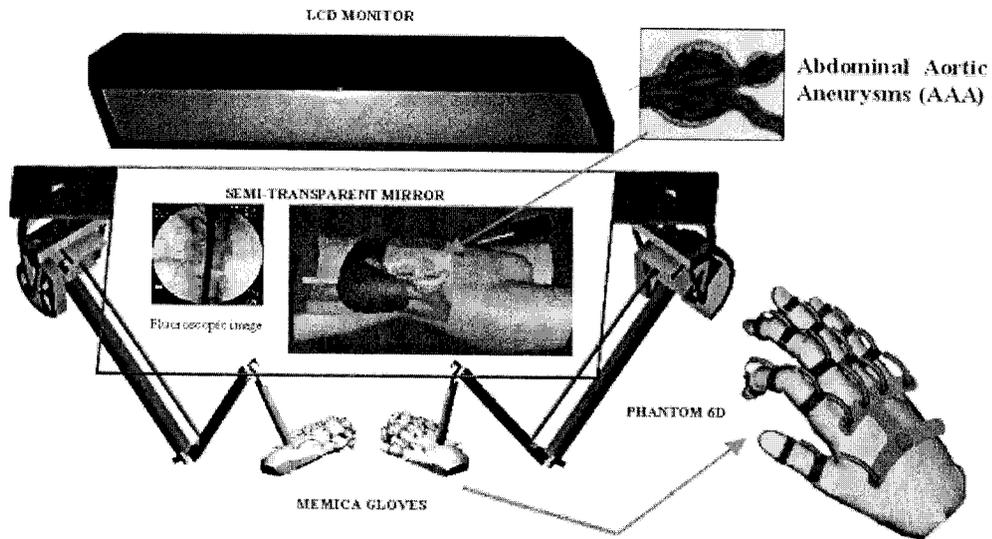


**FIGURE 11:** Robotic hand (Photographed at JPL) is available at JPL as a platform for demonstration of EAP actuators [Courtesy of Dr. Graham Whiteley, Sheffield Hallam U., UK. The actuators were installed by Giovanni Pioggia – University of Pisa, Italy/JPL].

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, 2001a]. Making insect-like robots could help inspection hard to reach areas of aircraft structures where the creatures can be launched to conduct the inspection procedure and download the data upon exiting the structure.

### **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. To address this need, the engineering community has started developing haptic (tactile and force) feedback systems. Users of future NDE simulators may immerse themselves in the display medium while being connected thru haptic and tactile interfaces to allow them to “feel the action” at the level of their fingers and toes. Thus, an expert can perform an NDE without from the convenience of the office without having to be present at the operation site. Recently, the potential of making such a capability was enabled with a very high resolution and large workspace using the novel MEMICA system (remote MEchanical MIRroring using Controlled stiffness and Actuators) [<http://ndea.jpl.nasa.gov/nasa-nde/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 Electrically Controlled Force and Stiffness (ECFS) actuators. Using this system, the feeling of the stiffness and forces applied at remote or virtual environments are reflected to the users via proportional changes in ERF viscosity. In Figure 12, a graphic presentation is shown of a MEMICA system for the simulation of an abdominal aortic aneurysm surgery. Using such a system the surgeon may be able to conduct a virtual surgery via virtual reality display while “feeling” the stiffness and forces that are involved with the procedure. Once low cost systems are developed such a capability may be applied to perform or practice inspection of aircraft and other structures while being in a classroom.



**FIGURE 12:** Performing virtual reality medical tasks via the Electro-Rheological Fluid based MEMICA haptic interface offers the potential of highly attractive interactive simulation system.

### SUMMARY AND OUTLOOK

Technologies that allow developing biologically inspired system are increasingly emerging. Such robots may perform combinations of locomotion techniques including walking, hopping, swimming, diving, crawling, flying, etc. with selectable behavior and performance characteristics. Making robots that are actuated by electroactive polymers, namely artificial muscles that are controlled by artificial intelligence would create a new reality with great potentials to NDE. Electroactive polymers have emerged with great potential enabling the development of unique biologically inspired devices. As artificial muscles, they are offering capabilities that are currently considered science fiction. Enhancement of the performance of EAP will require advancement in related computational chemistry models, comprehensive material science, electro-mechanics analytical tools, and improved material processing techniques. Using effective EAP actuators to mimic nature would immensely expand the collection and functionality of robots that are currently available. Important addition to this capability can be the application of tele-presence combined with virtual reality using haptic interfaces that employ the ERF-based MEMICA system. While such capabilities are expected to significantly change future robots, additional effort is needed to develop robust and effective EAP-based actuators.

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. 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 having a match between EAP-actuated robots and a human opponent 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 benefit NDE in many forms including the development of robots that operate as artificial inspectors.

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