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ENABLING NOVEL SPACE AND TERRESTRIAL APPLICATIONS USING TRANSDUCING MATERIALS

Yoseph Bar-Cohen, Xiaoqi Bao, Zensheu Chang and Stewart Sherrit
Jet Propulsion Laboratory/Caltech, Pasadena, CA 91109

ABSTRACT

Transducing materials are being used in many aspects of our daily life serving as actuators, sensors, displays, communications and other components of commercial mechanisms. At JPL, such materials are being used to enable novel space and terrestrial applications. This effort involves mostly the use of piezoelectric, electroactive polymers (EAP), and shape memory alloys (SMA). The piezoelectric based devices and mechanisms that were developed include ultrasonic motors, piezopump, ultrasonic/sonic driller/corer (USDC), whereas the electroactive polymers were used to demonstrate a gripper, wiper, lifter and haptic interfaces. The research involves analytical modeling, experimental corroboration, material characterization and device/mechanism design, construction and demonstration. The effort is multidisciplinary requiring expertise that is complemented through international cooperation. The research team activity will be reviewed in this paper.

INTRODUCTION

Actuators are a key element of many space exploration systems and they consume a sizeable percentage of the volume, mass, and power of planetary missions. Efforts are underway to reduce these parameters by improving existing actuation technology and implementing new materials. The JPL's Non Destructive Evaluation and Advance Actuators (NDEAA) Technologies laboratory [http://ndeaa.jpl.nasa.gov] is involved with research and development of novel actuation materials and mechanisms that are enabling new possibilities in future missions. This activity enjoys technical contributions from partnerships and cooperation with researchers and engineers from academia, government and industry both in the US and worldwide. The NDEAA team activity has evolved from NDE related R&D [Bar-Cohen, 2000] to a broad range of mechanisms and devices taking advantage of acoustic or elastic waves and the capabilities of the transducing materials that generate them. These efforts cover a wide spectrum of frequencies and amplitudes as shown in table 1. The mechanisms and devices that are developed by NDEAA include ultrasonic motors, piezopumps that are driven by traveling flexural waves [Bao and Bar-Cohen, 2000; Bar-Cohen and Chang, 2001]. Using a piezoelectric stack actuator, an ultrasonic driller and corer [Bao, et al, 2002] is being developed for potential applications at high temperatures as expected on Venus and low temperatures as on Mars, Titan or Europa. In parallel, electroactive polymers (EAP) are being investigated for use as actuators that mimic muscles earning them the name artificial muscles. A four-fingers gripper was constructed and demonstrates to lift a rock. Also, wipers driven by these materials were developed to remove dust from optical components. These wipers operate in a similar manner to windshield wipers but with a simplified mechanism. These wipers were also demonstrated as a cleaning mechanism for wet sensors used in water reclamation systems. EAP materials are also being investigated for potential use in shape control of membrane/gossamer structures. In addition, the team is also involved with the exploration of focused high power ultrasonic waves methods for medical treatment applications [Grandia and Bar-Cohen, 1998]. In this manuscript, the actuators that are being developed at the NDEAA Technologies lab of JPL are reviewed.

TABLE 1: NDEAA technologies categorized by the acoustic and elastic wave frequency and amplitude range.

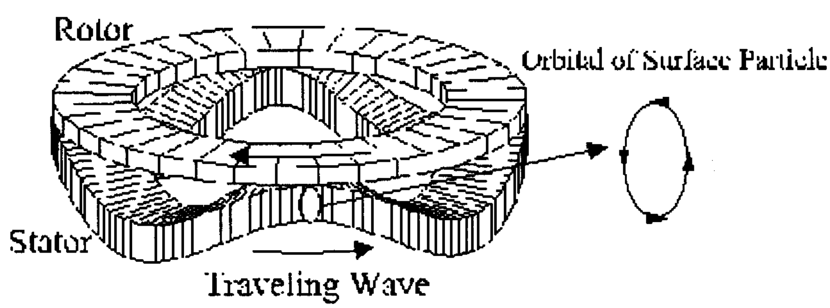
	Low amplitude	*High amplitude*
Low frequency (Hz - KHz)	Sonotomography	Actuation, drilling/coring
High frequency (KHz - MHz)	NDE & diagnostics	Medical treatment

ULTRASONIC MOTORS

Ultrasonic plate waves can be harnessed to provide actuation forces in the form of ultrasonic motors that have the potential to meet NASA needs. Generally, ultrasonic motors [Wallashek, 1995] can be classified by their mode of operation (static or resonant), type of motion (rotary or linear) and shape of implementation (beam, rod, disk, etc.). Despite the distinctions, the fundamental principles of solid-state actuation tie them together: microscopic material deformations (usually associated with piezoelectric materials) are amplified through either quasi-static mechanical or dynamic/resonant means. Several of the motor classes have seen commercial application in areas needing compact, efficient, and intermittent motion. Such applications include camera auto-focus lenses, watch motors and compact paper handling. Obtaining the levels of torque-speed characteristics of USMs using conventional motors requires adding a gear system to reduce the speed, thus increasing the size, mass and complexity of the drive mechanism. USMs are fundamentally designed to have a high holding force, providing effectively zero backlash. Further, since these motors are driven by friction, the torque that would cause them to be back-driven at zero power is significantly higher than the stall torque. The number of components needed to construct ultrasonic motor is small minimizing the number of potential failure points. The general characteristic of USMs makes them attractive for robotic applications where small, intermittent motions are required.

In Figure 1 the principle of operation of an ultrasonic motor (flexural traveling wave ring-type motor) is shown as an example. A traveling wave is established over the stator surface, which behaves as an elastic ring, and produces elliptical motion at the interface with the rotor. This elliptical motion of the contact surface propels the rotor and the drive-shaft connected to it. Teeth on the top section of the stator are intended to form a moment arm to amplify the speed. The operation of USM depends on friction at the interface between the moving rotor and stator, which is a key issue in the design of this interface for extended lifetime.

FIGURE 1: Principle of operation of a rotary flexural traveling wave motor.



The use of USMs in NASA application requires operation at harsh space environments that include cryogenic temperatures and vacuum and also require effective analytical tools for the design of efficient motors. To explore telerobotic applications for USMs a robotic arm was constructed with such motors. A hybrid finite element analytical model was developed to examine the excitation of flexural plate wave traveling in a piezoelectrically actuated rotary motor [Bao and Bar-Cohen, 2001]. The model uses 3D finite element and equivalent circuit models that are applied to predict the excitation frequency and modal response of the stator. This model incorporates the details of the stator including the teeth, piezoelectric ceramic, geometry, bonding layer, etc. A brush model is used for the interface layer and Coulomb's law for the friction between the stator and the rotor. The theoretical predictions were corroborated experimentally for the motor as shown in Figure 2, where a 1.18" diameter by 0.44" thick prototype motor was developed and demonstrated to deliver a stall torque of 1 inch-lb.

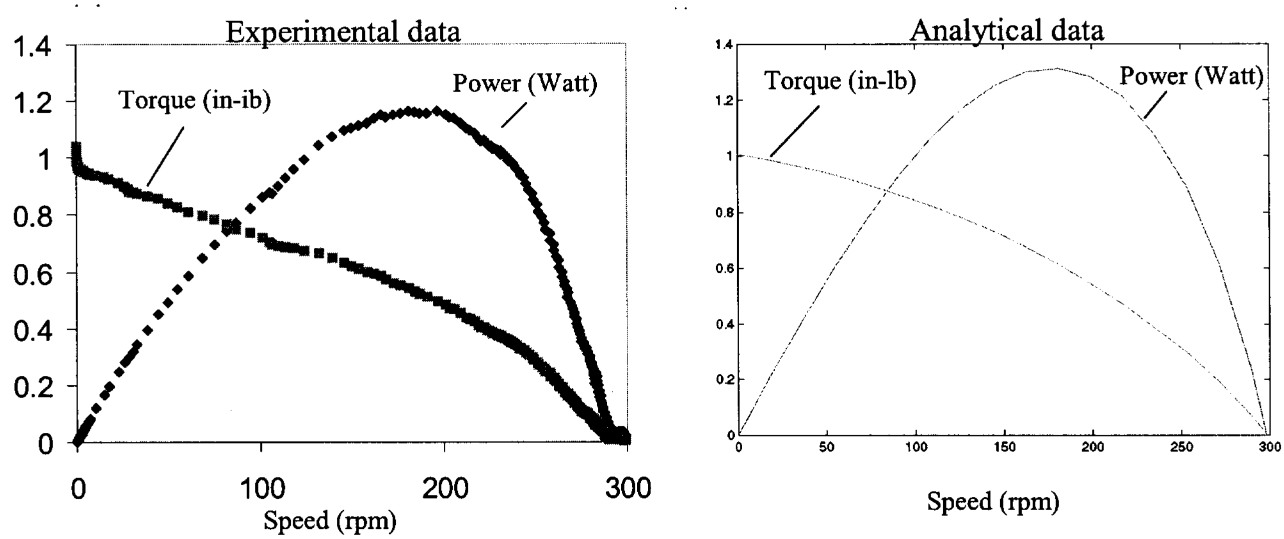


Figure 2: Torque and power versus speed performance of a 1.18" diameter by 0.44" thick USM

The model uses 3D finite element and equivalent circuit models that are applied to predict the excitation frequency and modal response of the stator. This model incorporates the details of the stator including the teeth, piezoelectric ceramic, geometry, bonding layer, etc. The theoretical predictions were corroborated experimentally for the stator. In parallel, efforts have been made to determine the thermal and vacuum performance of these motors. Experiments have shown that the motor can sustain at least 230 temperature cycles from 0°C to -90°C at 7 Torr pressure significant performance change. Also, the motor lasted over 334 hours at -150°C and vacuum. To examine the cause of failure, an ultrasonic C-scan nondestructive test was made and the discontinuities were imaged on the computer monitor. As anticipated, the bond between the stator and piezoelectric ring wafer failed. The continuous piezoelectric ring that drives the stator is subjected to thermal stresses that are aggravated by the cyclic mechanical loading of the motor operation leading to fatigue failure of the bond line. In cooperation with QMI, JPL replaced the continuous ring with segmented and reversed piezoelectric drive (SRPD) wafers allowing to effectively relief the thermal and dynamic stresses at the bonding layer.

To demonstrate the viability of USM a robotic arm with a scoop was developed using such motors to manipulate the arm from a lander mockup. Further, a Multifunction Automated Crawling System (MACS) was constructed using an arrangement of two sets of legs and suction cups for operation on aircraft fuselage and other structures [Bar-Cohen, et al, 1999]. MACS was equipped with USMS to allow its mobility and in Figure 3 it is shown attached to the fuselage surface of the military aircraft C-5.

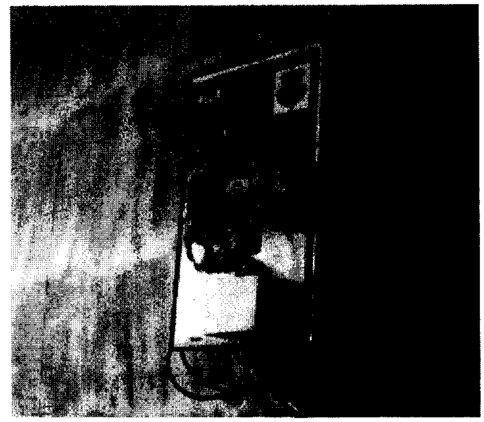


FIGURE 3: Driven by USMs, the Multifunction Automated Crawling System (MACS) on the C5

PIEZOPUMP

Pumps are used for a wide variety of applications including thermal management, cooling systems, mass spectrometers, vacuum-controlled devices, and compressors. NASA is increasingly becoming involved with surface sampling missions and *in-situ* remote analysis where there is a need to move liquids to and inside instruments. The pumps are required to transport liquids, which potentially contain bacteria and other microorganisms, through filter media and the displaced volume can be as low as milliliters. Studies of wave travel on the stator of an ultrasonic motor are showing the potential to produce a pump using the traveling valleys as boxcars. Covering these valleys allows forming chambers that can carry liquids operating as a peristaltic pump [Bar-Cohen and Chang, 2001]. Such piezopump eliminates the need for valves or physically moving parts and there are various instruments and applications for which such miniature pumps are needed.

A finite element model was developed using ANSYS for the purpose of predicting the resonance frequency of the vibrating modes of the piezopump driving stator. The model allows determining simultaneously the mode shapes that are associated with the various resonance frequencies. This capability is essential for the design of the pump size and geometry. To predict and optimize the pump efficiency that is determined by the volume of pumping chambers the model was modified to perform harmonic analysis. Current capability allows the determination of the effect of such design parameters as pump geometry, construction materials and operating modes on the volume of the chambers that are formed between the peaks and valleys of the waves. Experiments performed by using a piezopump breadboard showed water-pumping rate of about 4.5-cc per minute with the highest-pressure level of 1100 Pascal. The pump is continually being modified to enhance the performance and efficiency. In Figure 4, a photograph shows a prototype piezopump pumping water.

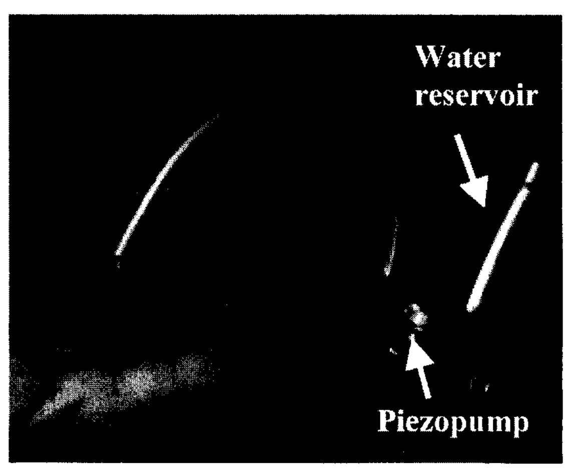


FIGURE 4: A view of piezopump in action.

ULTRASONIC/SONIC DRILLING/CORING (USDC)

NASA's Mars and Solar System exploration missions are seeking to perform in-situ analysis of samples from the various depths on a number of celestial bodies. The environments that these instruments are expected to face range from cryogenic (Comets) to very hot and aggressive (Venus). Geological surveys from a lander or a rover require instrumented samplers to be placed at the end of a flexible arm or on a very-light rover. Low mechanical impact on the host platform is a major requirement for these samplers. Planetary sampling using conventional drilling and coring techniques is limited by the need for high axial force necessitating the use of heavy rovers or anchoring mechanisms. Recently, the authors and Cybersonics, Inc. developed the ultrasonic/sonic driller/corer (USDC) [Bao, et al, 2002; Bar-Cohen, et al, 2001; and Sherrit, 2000] overcoming these and other limitations of conventional techniques. The USDC drill consists of three components: actuator, free-mass and bit. A schematic diagram of the USDC mechanisms is shown in Figure 5. The novel elements of the USDC are the drilling/coring bit and the free-mass that operates as a frequency transformer converting 20KHz ultrasonic waves to a 60-1000 Hz sonic hammering action (percussion). The USDC actuator consists of a stack of piezoelectric ceramics with a backing material that focuses the emission of the acoustic energy forward, and a horn that amplifies the displacements generated by the stack. The tip of the ultrasonic horn impacts the free-mass creating a sonic resonance between the horn and the bit.

The USDC has been demonstrated to drill rocks that range in hardness from basalt to soft sandstone and tuff. Other media that have been drilled include soil, ice and diorite, and limestone. This novel drill is capable of high-speed drilling (2 to 20-mm/Watt·hr for a 2.85mm diameter bit) in basalt and Bishop Tuff using low axial preload (<10N) and low average power (<5W). This capability to drill with minimal load is presented in Figure 6, where the drill is shown in operation while being held from its power cord. It drilled 25-mm deep, 6-mm diameter holes in basalt in a little over 2-hrs from a 4-kg platform using 10W average and 25W peak power. It also drilled 15-cm deep, 5-mm diameter holes in sandstone in just over an hour using similar power as for the basalt drilling. The USDC mechanism has demonstrated feasibility for deep drilling using a novel device called Ultrasonic-Gopher (Figure 7) that can potentially be used for deeper drilling.

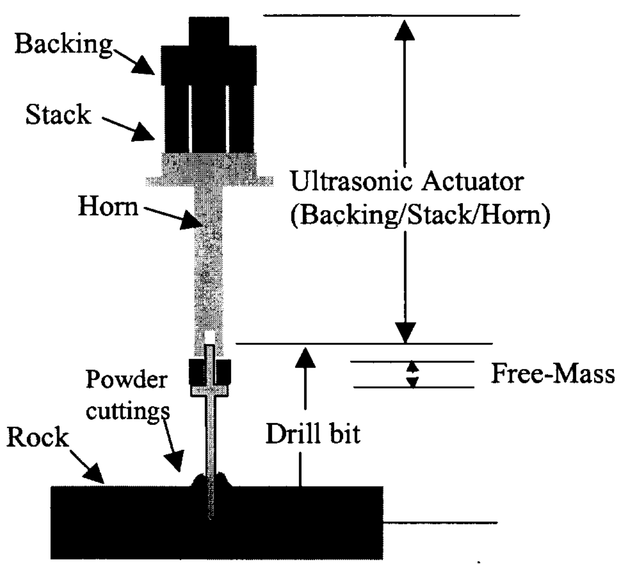


FIGURE 5: A schematic view of the USDC components

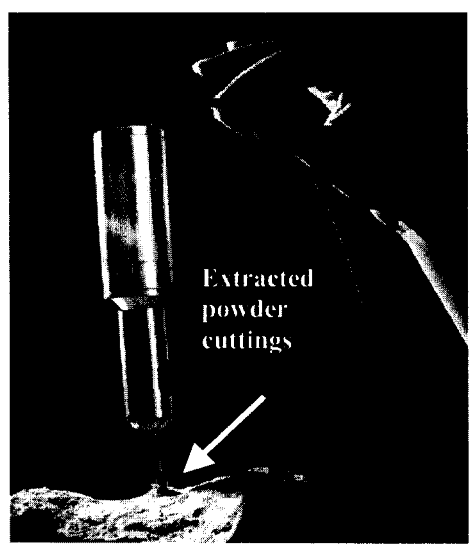


FIGURE 6: The USDC is shown to require relatively small preload to core a rock. The powder cuttings travel along the bit providing a removal mechanism for acquisition.

Generally, the USDC bit creates a borehole that is larger than the drill bit outer diameter and it also creates a core that is smaller in diameter than the inner diameter of the coring bit. This reduces the chances of bit jamming while hole integrity is maintained, and it eases in the extraction of the core from the bit. Current analytical models suggest that the USDC performance does not change significantly with changes in ambient gravity.

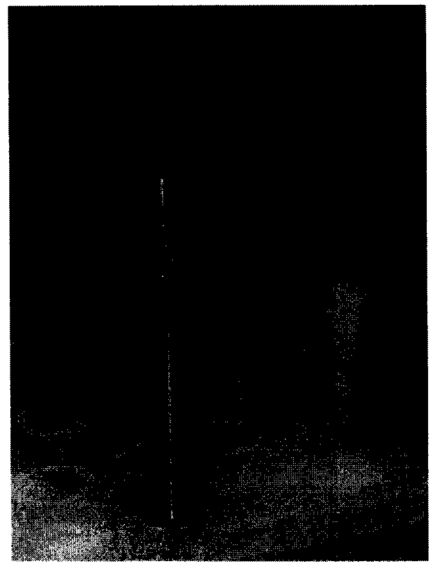
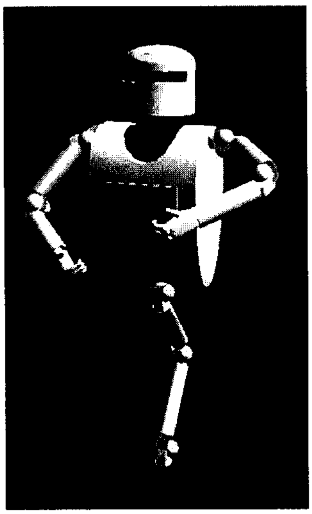


FIGURE 7: An Ultrasonic-Gopher and an extracted core (on the right) from a limestone.

INTERACTIVE AND INTUITIVE MIRRORING OF COMPLIANCE AND FORCES

For many years, the robotic community sought to develop robots that can operate complex tasks autonomously to eliminate the need for human operators. However, there is an increasing realization that humans can perform some tasks significantly better but, due to associated hazards, distance, physical limitations and other causes, only robots can be employed to perform these tasks. Remotely performing such tasks by robots operating as human surrogates is referred to as telepresence. In telepresence the operator receives sufficient information about the remote robot and the task environment is displayed in a sufficiently natural way, that the operator would be able to feel the equivalent of physical presence at the remote site. Haptic feedback is necessary for a telepresence system where physical constraints such as object rigidity, mass and weight, friction, dynamics, surface characteristics (smoothness or temperature) are mirrored to the human operator from the remote site.

Robots capability to operate as a surrogate human has been developed at NASA Johnson Space Center as the novel space robot called Robonaut, i.e., robotic astronaut (see Figure 8) [http://tommy.jsc.nasa.gov/robonaut/Robonaut.html, 1997]. This robot was developed to perform extra-vehicular activity (EVA) to allow rapid deployment with ability to maneuver through areas that are too small for the current Space Station robots. Robonaut was developed to support high-payoff EVA tasks and to provide "minuteman"-like responses to EVA contingencies. The Robonaut was designed as an anthropomorphic robot, similar in size to a suited EVA astronaut and as a telepresence system that immerses the remote operator into the robot's environment. Its robotic arms are capable of dexterous, human-like maneuvers and are designed to ensure safety and mission success. Its robotic hands are designed to handle common EVA tools, to grasp irregularly shaped objects, and to handle a wide spectrum of tasks requiring human-like dexterity. Robonaut was designed so that a human operator who is wearing gloves/suit with sensors can control it. If the user is to interact in a natural way with the robot, the interface must be intuitive, accurate, responsive, transparent and reproducible over time and space. Furthermore, the operator must be able to extract information about the robot and its environment to effectively control the robot. Unfortunately, due to limited availability of force and tactile feedback capability in the control suit/glove, the operator determines the required action by visual feedback, i.e. looking at the Robonaut action at the remote site. This approach is ineffective and limits the potential tasks that Robonaut can perform.



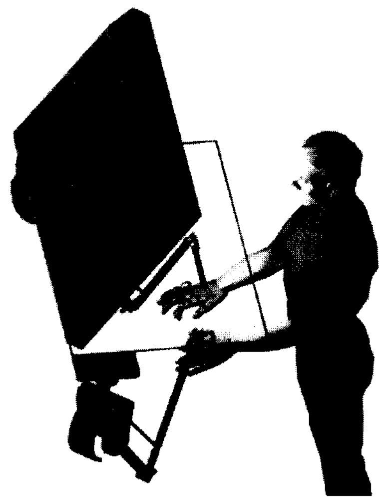


FIGURE 8: Robonaut **FIGURE 9:** Performing virtual task via a MEMICA as a Haptic Interface

To address the need for telepresence, a haptic interfacing mechanism is required to allow operators to "feel" the stiffness and forces at remote or virtual sites (See Figure 9). For this purposed the JPL's NDEAA has teamed with investigators from Rutgers University conceived a system that is called MEMICA (remote MEchanical MIrroring using Controlled stiffness and Actuators) [Mavroidis, et al, 2001] The key aspect of the MEMICA system is a miniature Electrically Controlled Stiffness (ECS) element that mirrors the stiffness at remote/virtual sites. The ECS elements make use of Electro-Rheological Fluid (ERF), which is an Electro-Active Polymer (EAP), to achieve the feeling of remote or virtual stiffness. The ECS elements will be placed at selected locations of an instrumented glove to mirror the forces of resistance to motion at the corresponding locations of the robot hand. Forces applied at the robot end-effector due to a compliant environment will be reflected to the user with the aid of this ERF device where a change in the system viscosity will occur proportionally to the force to be transmitted. The MEMICA system also consists of Force Feedback Actuation Tendon (FEAT) elements, which employ other type of actuators to mirror forces induced by active elements at the remote or virtual site.

ELECTROACTIVE POLYMERS ACTUATORS - ARTIFICIAL MUSCLES

During the last ten years, 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. This capability of the new electroactive polymers (EAP) attracted the attention of engineers and scientists from many different disciplines. Since these materials behave similar to biological muscles, they have acquired the moniker "artificial muscles" [Bar-Cohen, 2001]. Practitioners in biomimetics, a field where robotic mechanisms are developed based on biologically-inspired models, are particularly excited about these materials since they 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 [Bar-Cohen and Breazeal, 2002].

For several decades, it has been known that certain types of polymers can change shape in response to electrical stimulation. Initially, these EAP materials were capable of inducing only a relatively small strain. However, since the beginning of the 1990s, a series of new EAP materials has been developed that can induce large strains leading to a great change in the view of the capability and potential of these materials. Generally, EAPs can induce strains that are as high as two orders of magnitude greater than the striction-limited, rigid and fragile electroactive ceramics (EAC). Further, EAP materials are superior to shape memory alloys (SMA) in that they possess higher response speed, lower density, and greater resilience. The current limitations of EAP materials include low actuation force, mechanical energy density and robustness limit the scope of their practical application.

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, though SPIE International as part of the Smart Structures and Materials Symposium. 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. Following this success, a Materials Research Society (MRS) conference was initiated to address fundamental issues related to the material science of EAP. The SPIE conferences are now organized annually and have 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, and a semi-annual Newsletter is issued electronically.

The increased resources, the growing number of investigators conducting research related to EAP, and the improved collaboration among developers, users, and sponsors is expected to lead to rapid progress in the coming years. In 1999, the author posted a challenge to the worldwide community of EAP experts to develop a robotic arm that is actuated by artificial muscles to win an arm wrestling match with a human opponent (Figure 10). 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, potentially leading to a "bionic human." A remarkable contribution of the EAP field would be to one day see a disabled person jogging to the grocery store with the aid of this technology.

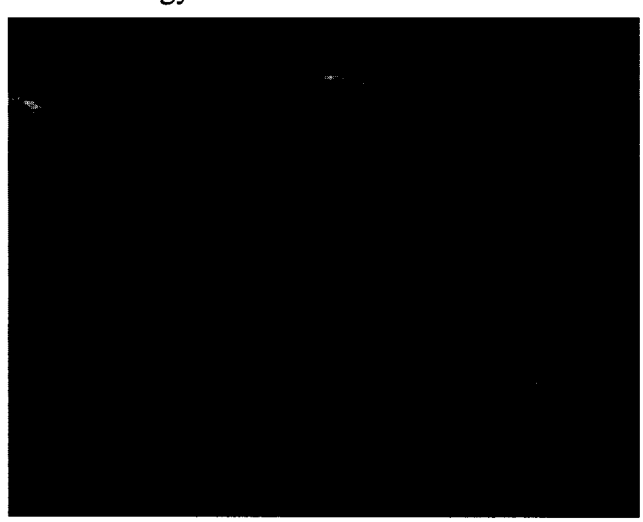


FIGURE 10: Grand challenge for the development of EAP actuated robotics

CONCLUDING REMARKS

Time dependent elastic motion offers diagnostics and actuation capabilities that enable novel technologies that can benefit many fields including planetary exploration, medical, military and industry. The JPL's NDEAA team have taken ultrasonic waves and developed unique capabilities to support various technologies that include robotics, NDE, manipulation mechanisms, haptic interfaces, etc. Finite element modeling tools and experimental capabilities were developed to support the required design tools. The actuators and devices that were developed include an ultrasonic motor that can operate in vacuum and cryogenic temperatures, piezopump of peristaltic pumping no physically moving parts, an ultrasonic drill that can be used to sample rocks using very low axial load with no lubricants and the bit does not require sharpening. Moreover, a haptic interface system was conceived that enables virtual operations as well as performing telepresence with the aid of such robots as the Robonaut. Using polymers that are electroactive actuators that emulate muscles are being developed and employed in various devices that are compact, low mass, and low power. These actuators are being considered for such applications as gossamer structures and biologically inspired mechanisms..

ACKNOWLEDGEMENT

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