WorldWide ElectroActive Polymers


EAP

(Artificial Muscles) Newsletter

June 1999 **WW-EAP Newsletter** **Vol. 1, No. 1**

http://ndeaa.jpl.nasa.gov/nasa-nde/lommas/eap/EAP-web.htm

FROM THE EDITOR

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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. Their main attractive characteristic 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 technologies. 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 this topic of EAP. It marked an important milestone for this field and turned the spotlight onto these emerging materials and their potential. Further, this WW-EAP Newsletter was initiated to bring the world-wide EAP community even closer.

A challenge was posed to the EAP science and engineering community to develop a robotic hand that is actuated by EAP and able to win against a human in an arm wrestling match. 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" of the future. My hope is to someday see a handicapped person jogging to the grocery store using this technology.

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GENERAL NEWS

In 1999, the field of EAP has rapidly evolved to become an internationally established activity. Two annual conferences are now in place: SPIE (in March)- covering actuators and devices, and MRS (in November) - covering material science. Moreover, two forums of communication were initiated: the WW-EAP Newsletter and the EAP Worldwide Website.

SPIE Conference

In recognition of the need for international cooperation among developers, users and potential sponsors, an SPIE Conference was organized for the first time on March 1-2, 1999, in Newport Beach, California. This was the largest conference ever held on the topic of EAP involving about 150 scientist and engineers. Besides the technical exchange, one of its major achievements was the turning of the spotlight onto these emerging materials and their potential.

49 papers and posters were presented and the conference was well attended by leading world experts and participants who have an interest in EAP. The attendees consisted of individuals from academia, research institutes, industry, and government agencies in the USA and overseas. The conference was followed by a session entitled "EAP in Action," which was intended to give the participants hands-on experience with the various state-of-the-art EAP materials. The proceedings of the conference were issued in early June, and are now available from SPIE. The next SPIE conference on EAP will be held on March 5-6, 2000. It will be held as part of the 7th International SPIE Symposium on Smart Structures and Materials. Abstracts are due on *9 August 1999*. For further information please see:
http://www.spie.org/web/meetings/calls/ss00/ss04.html

MRS Meeting

To address issues related to the material science of electroactive polymers, a Symposium FF, was organized by Qiming Zhang, Takeo Furukawa, Yoseph Bar-Cohen, and Jerry Scheinbeim. This Symposium is part of the MRS Fall 1999 Meeting and it will be held in Boston, Massachusetts from Nov. 29 to Dec. 3, 1999. The abstracts were due by June 21 and 75 were submitted (a record number). Some of the topics that will be covered include ferroelectric polymers, polymer composites, polymer gels, and thin polymer films for applications in smart materials, actuators, transducers, and micro-electronics. For more information please see http://www.mrs.org/meetings/fall99/

WW-EAP NEWSLETTER

This WW-EAP Newsletter was formed to provide a timely update and technical communication platform. Efforts are made to solicit input worldwide from experts who are developing new mechanically active polymers and related processes, improving our understanding of these materials and their electro-mechanical/ chemical characteristics, exploring new applications, investigating the relationship between EAP and biology and others. The input format is as an abstract accompanied by contact name, e-mail address and optional graphics.

EAP Worldwide Website

To further enhance international collaboration among the EAP developers, users and interested individuals a web-hub was formed (address: http://ndeaa.jpl.nasa.gov/nasa-nde/lommas/eap/EAP-web.htm) This web-hub contains general information, archive and links to research organizations that are active in the field of EAP.

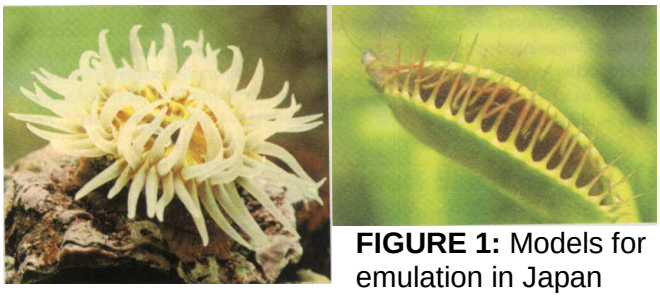

FIGURE 1: Models for emulation in Japan

Advanced Stimuli-Responsive Materials

In 1996, an Advanced Stimuli-Responsive Materials program was established in Japan with the objective of developing industrial materials that intellectually emulate environmental responsive functions of biological systems. This program is sponsored by the Ministry of International Trade & Industry (www.nedo.go.jp) program - Industrial Science and Technology

Frontier. The objective is to develop artificial muscles through technical cooperation among industry and academia within and outside Japan. The technology steering committee coordinator is Yoshihito Osada and his address is:
osada@sci.hokudai.ac.jp

Multifunctional & Smart Polymer Systems

This is an annual meeting that addresses multifunctional polymer-related topics including EAP. The 4th workshop is organized by the Biomedical Environmental Sensor Technology Center in Dublin, Ireland. It will be held from Sept. 20 - 23, 1999. Abstracts are due on June 30. The previous workshops were held in Lower Hutt, New Zealand (1996); Wollogong, Australia (1997); and Pisa, Italy (1998). For further information contact Gordon Wallace
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AUSTRALIA

WOLLONGONG UNIVERSITY

Advances in Polymer Actuators

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The configuration of "solid state" polymer actuators consisting of gold-PPy-solid ion source/ sink-PPY-gold film is under investigation in our laboratory, IPRI. The performance of such devices has recently been described in the references listed below. Currently the work at our laboratory is focused on the optimization of these actuators. This has involved the following studies.
(1) *Electrochemical processes* - It is important to understand that the conductivity of ICPs changes dramatically as they are oxidized and reduced. This effort is seeking to take advantage of the presence of two-polymer electrode actuators. The increased resistance upon electrochemical reduction causes a potential drop that lowers the potential applied between the electrodes, preventing over-oxidation of the other component of the device. Optimization of the potential difference enables repetitive stimulation of the all-polymer actuator to be carried out with no loss in performance. (Submitted for publication in Journal of Synthetic Metals).

(2) *Device configuration* - The performance of all-polymer devices is limited by the diffusion of ions in/out of the polymer. This is determined by the composition of the active polymer electrodes and solid polymer electrolyte (ion source/sink) and by the device configuration. Recently, we have shown that the use of polymer-coated PTFE fibers as active electrodes increases the force densities achievable by an order of magnitude compared with the use of simple conducting polymer films. (To appear in Journal of Synthetic Metals).

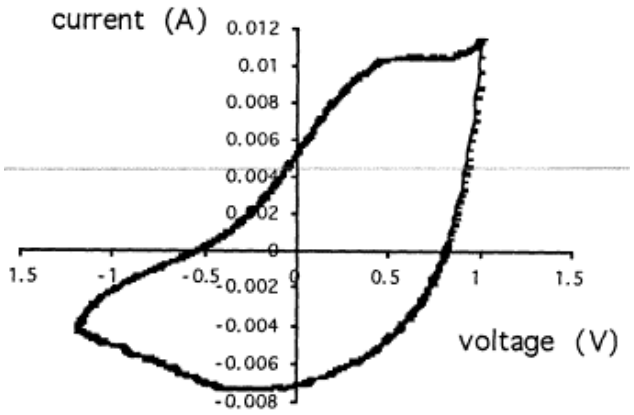

FIGURE 2: Cyclic voltammogram of PPy-SPE-PPy sandwich against a Ag/AgCl reference at 10 mV/sec. PPy/ClO_4/pTS films as working and counter electrodes, and PAN/PC/EC/$NaClO_4$ as SPE.

(3) *New polymer actuator materials* - In parallel, we have developed synthesis protocols for a number of novel polythiophenes. These materials have excellent mechanical properties and importantly, as far as polymer actuators are concerned, have a wide electrochemical potential window.
(4) *Novel solid polymer electrolytes* - As active ICP electrode materials are optimized, the performance (ionic conductivity, mechanical properties, environmental stability) of the SPE becomes the limiting factor in determining the performance efficiency of all polymer actuator devices. Our studies involve a range of solid polymer electrolyte (e.g., polyacrylonitrile, Kynar, polyvinyl alcohol) and hydrogel (e.g., polyacrylamide) ion sources/sinks. Figure 2 shows the CV obtained from one such device that utilizes a polyacrylonitrile based solid polymer electrolyte.

References:
Lewis, T.; Spinks, G.; Wallace, G.; De Rossi, D.; Pachetti, M., *Polymer Preprints*, 38(2), (1997) 520.
Lewis, T.; Moulton, S.; Spinks, G.; Wallace, G, *Synthetic Metals*, 85, (1997) 1419.
Lewis, T.; Kane-Maguire, L.; Hutchison, A.; Spinks, G.; Wallace, G., *Synthetic Metals* (In Press).

JAPAN

HOKKAIDO UNIVERSITY

Chemical Motor Driven by Immersing Polymer Gel in Organic Solvent

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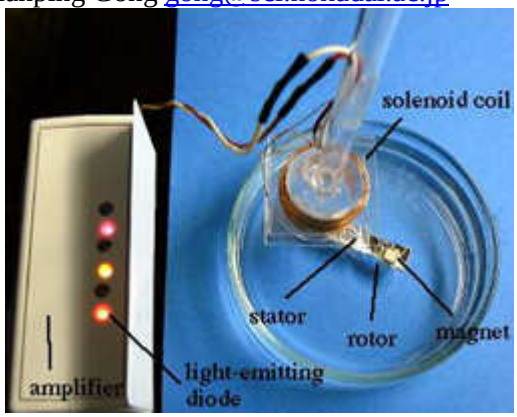

FIGURE 3: Experiment using generator in organic solvent impregnated with gel.

Yoshihito Osada and his research team of Division of Biological Sciences, Graduate School of Science, Hokkaido University, have developed a chemical motor that obtains its rotary force by immersing a polymer gel in an organic solvent such as alcohol (Figure 3). When a gel with absorbed organic solvent is floated on water, the absorbed organic solvent is discharged and becomes active immediately and continuously. This phenomenon is utilized as an EAP motor and by feeding the gel continuously with the organic solvent, the chemical motor continues to revolve infinitely. The research team observes that there is a great possibility of utilizing this chemical motor as a pollution-free "fuel battery" that uses alcohol for regeneration as the energy source.

The research team opened small grooved holes on both terminals of the rotor to accommodate the polymer gel, packed polystearile acrylate (PSA) gel there, and followed with the addition of alcohol. The grooved holes at both terminals are positioned in opposite directions, so when the rotor is floated on water, it starts revolving with the stator as its axis. The rotary speed of this chemical motor is changed radically with the motor's mass, and with an experimentally fabricated motor of 25-mg, a maximum speed of 400-rpm was attained. Without supplementation of organic solvent, the motor revolved for a maximum of three hours. In an experiment in which a generator was connected to convert the chemical motor's rotary energy into electric energy, an instantaneous electromotive force of maximum 15-millivolts and power of 2.1 x 10^{-7} joules were obtained. This corroborated that chemical energy can be converted directly into motional energy, and then further into electric energy.

OSAKA NATIONAL RESEARCH INSTITUTE

Electroactive Tubular Actuator

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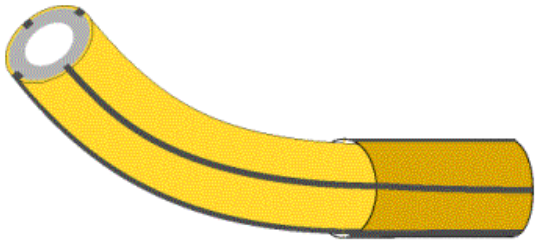

FIGURE 4: Active Catheter guide using the bending EAP type IPMC.

The joint research group of Osaka National Research Institute and Japan Chemical Innovation Institute has developed an electroactive bending tube made of an ion-exchange polymer tube and gold electrodes (Figure 4). The gold electrode plated on the outer surface of the tube was divided to four strips in parallel with the axis. The tubular actuator (0.6 mm in outer diameter and 15 mm in length) bends over 90 degrees for all directions by 3 V electric stimuli between the electrode pairs. It works as the tip of an active micro catheter for intravascular surgery.

SHINSHU UNIVERSITY

Polymer Gel Generating Bending and Crawling Motion

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Nonionic polymer gel swollen with dielectric solvent shows tremendous action in air by applying a dc electric field (Figure 5). Poly(vinyl alcohol) gel swollen with dimethyl sulfoxide showed swift bending and crawling motion under the electric field. The gel used is 10-mm in length, 3-mm in width, and 2-mm in thickness. A bending angle of 90 degree was attained within 60-ms when the field was applied on both surfaces of the gel. The gel stripe could crawl on the array of the stripe electrodes. These phenomena were explained by a charge injection into the gel and the flow of the solvated charge that can induce an asymmetric pressure distribution in the gel. This idea can be applied to conventional polymer materials. The motion is not only large in magnitude but also far quicker than any other electroactive polymer gel reported so far. (Reference: SPIE, Vol. 3669, 209-217 (1999)).

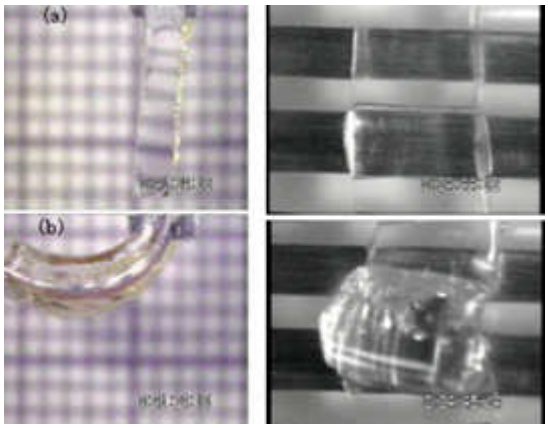

FIGURE 5: Polymer gel bending (left) and crawling (right).

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Conducting polymers based on bilayer polypyrrole-polymeric tapes are being investigated as artificial muscles in our laboratory. The flexible polymer tape bends as a result of reduction and oxidation processes that cause contraction and expansion, respectively. Using a 3x1.5-cm bimorph tape, 180º swings are observed in 4-6 seconds under current densities of 7-mA.cm^{-2}. Using triple layer polypyrrole-tape-polypyrrole, a steel ball that is several hundred times heavier was made to move when placed near the tip. When the movement is stopped, the tape position does not relax to the lowest mechanical energy stage, because it would require a parallel chemical or electro-chemical reduction of the polymer. Our actuator operates as both actuator and sensor. Moreover, by making a multi-layered polypyrrole sandwich the actuator was made to work in air.

A relaxation model integrating electro-chemistry and polymer science is being developed able to explain the "anomalous" (as named in previous literature) electrochemical responses of the conducting polymers, as well as the electrochemically stimulated molecular motor mimicking natural muscles. The influence of different chemical and electrical variables on both movement rates and lifetime (number of cycles) of the muscles has been studied. To address the need for high production rate for this material, our lab has developed a synthesis technique that allows mimicking inorganic metals. This includes electrodissolution and electrodeposition for producing the required conductive polymer.

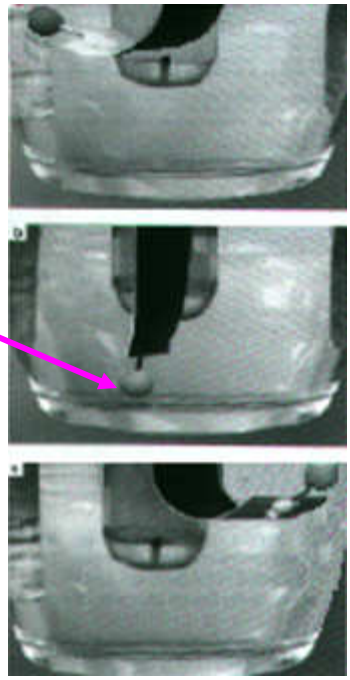

Figure 6: The bending actuator is sufficiently strong to move a steel ball.

Reference:

T. F., Otero, et al, EP-9200095, 1992.

T. F. Otero, et al, EP-9200095, 1992.

T.F. Otero & J. Rodríguez, M. Aldissi Ed., Kluwer Academic Publishers, Netherlands, 179-190, 1993.

T. F. Otero, Modern Aspects of Electrochemistry, 33, J. O'M. Bockris, R.E. White, B.E. Conway, Ed. Plenum Press, New York, 307-434, 1999.

TAIWAN

INDUSTRIAL TECH. RESEARCH INST.

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For many years, the main focus of the Division of Composite Materials of Materials Research Laboratories (MRL), at the Industrial Technology Research Institute (ITRI), has been on the industrial application of polymeric materials. This division accumulated extensive data and experience on materials selection, CAE simulation, structural design and product development. Recently, the focus of the efforts was shifted to include seeking applications for EAP actuators that can meet air flow needs of the computer, communication and consumer-electronic (3C) industries. This effort involves structural analysis and the development of new products. The MRL Division is receiving technical assistance and data from Hokkaido University and the University of Pisa including information about EAP materials density, modulus, strain, electrochemical strain coefficient, etc.

USA

ALLIED SIGNAL

Carbon Nanotube Artificial Muscles

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A new type of artificial muscle has been demonstrated by an international research team led by Ray Baughman of AlliedSignal that involves key researchers at the University of Florida (Gainesville), Georgetown University, the University of Wollongong (Australia), the University of Pisa (Italy), and the Max Planck Institute (Stuttgart, Germany). The team also includes Larry Dalton (Univ. Washington), Valy Vardeny (Univ. Utah) and Fotis Papadimitrakopoulos (Univ. Connecticut). Their latest success has been described in the May 21 issue of Science and is the subject of a pending patent application of AlliedSignal.

The new actuators are composed of carbon nanotubes having diamond-like mechanical properties. Reflecting the mechanical strength and modulus of the individual carbon nanotubes as well as the achievable actuator displacements, the new actuators have the potential of providing higher work per cycle than previous actuator technologies and of generating much higher mechanical stresses. Also, reflecting the high thermal stability of carbon, this new type of actuator might eventually be used at temperatures exceeding 1000 °C, which far exceeds the capabilities of alternative high-performance actuator materials.

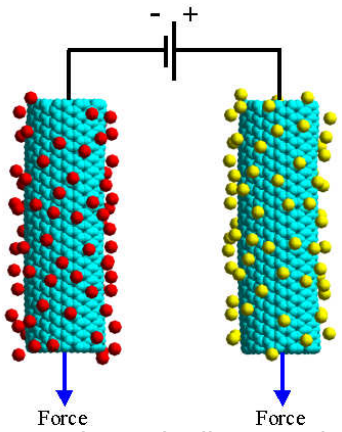

FIGURE 7: Schematic diagram showing electrochemical double layer charging of two carbon nanotubes and the force generated.

A carbon nanotube actuator can be constructed in about ten minutes by simply laminating together two narrow strips cut from a carbon nanotube sheet, using an intermediate adhesive layer which is electronically insulating. The resulting "cantilever device" is immersed in an electrolyte, such as a sodium chloride solution, and an electrical connection is made to the two nanotube strips. The application of about a volt bends the actuator in one direction, and reversing the potential bends the actuator in the opposite direction. Like bimetallic strips used for temperature regulation, this actuation depends upon the differences in expansion for the two-nanotube strips.

NOTE: Funded by DARPA grant N00173-99-2000 (under the EAP Program led by Dr. Steven Wax).

JPL

EAP Used to Develop a Dust-Wiper for MUSES-CN Mission to an Asteroid

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A team consisting of S. Leary, JPL; J. Harrison, J. Smith and J. Su, NASA-LaRC; T. Knowles, ESLI; in cooperation with K. Oguro, Osaka National Research Institute, Japan, and S.

Tadokoro, Kobe University, Japan, under the lead of Y. Bar-Cohen, is developing a dust wiper using a bending EAP actuator for the NASA/NASDA MUSES-CN mission. This dust-wiper is being developed for the infrared camera window of the mission's Nanorover (Figure 8). This joint NASA and Japanese space agency mission, is 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 the highly effective ion-exchange membrane metallic composites (IPMC) made of perfluorocarboxylate-gold composite with the 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 is powered with a high voltage to repel dust augmenting the brushing mechanism provided by the blade.

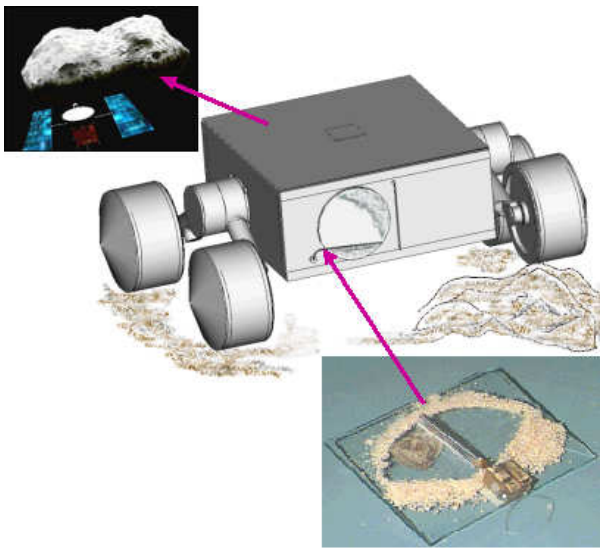

FIGURE 8: Schematic view of the EAP dust wiper on the MUSES-CN's Nanorover (right) and a photograph of a prototype EAP dust wiper (left).

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 operation in vacuum and low temperatures, as well as the effect of IPMC's electromechanical characteristics on its actuation capability. The use of highly effective IPMC materials, mechanical modeling, unique elements and a protective coating assures high probability of success for this IPMC actuated dust-wiper.

Cold Hibernated Elastic Memory (CHEM) Self-Deployable Structures

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FIGURE 9: Stowed and deployed CHEM structures.

The concept called “cold hibernated elastic memory” (CHEM) utilizes polyurethane-based shape memory polymers (SMP) in open cellular (foam) structures. The CHEM structures are self-deployable use the foam’s elastic recovery and shape memory to erect a structure. In practice, the CHEM foams are compacted to small volumes above their softening (glass transition) temperature Tg. They may then be stored below their Tg without constraint. Heating to a temperature above their Tg restores their original shape. The advantage of this exciting new technology is that structures, when compressed and stored below Tg, are a small fraction of their original size and are lightweight. Examples of stowed and deployed CHEM structures are shown in Figure 9.

The attractiveness of the CHEM structure is the wide range of Tg resulting in a variety of potential space and commercial applications. In commercial applications, the CHEM concept could be applied to shelters, hangars, camping tents, rafts or outdoor furniture to mention just a few. The CHEM parts can be transported and stored in small packages then expanded by heating at the outdoor site. After expansion, CHEM parts will be allowed to cool to ambient

temperature below their Tg, so that they become rigid as needed for use. CHEM foam materials are under development by the Jet Propulsion Laboratory (JPL) and Mitsubishi Heavy Industries (MHI). The CHEM structure technology was designed to be developed in 3 phases: Phase 1: Proof-of-CHEM concept (already completed), Phase 2: Characterization and sub-scale CHEM application development (present activities) and Phase 3: Full-scale CHEM application technology ground validation (future activities).

NASA-LaRC

Electrostrictive Graft Elastomers and Applications

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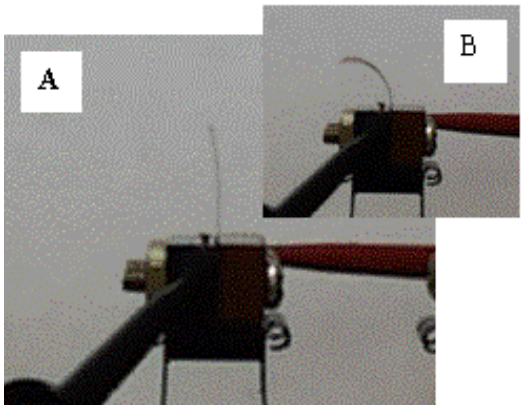

FIGURE 10: A bending actuator using the new electroactive graft elastomer (A) Under no applied voltage and (B) under applied voltage.

Recently, a new class of electro-mechanically active polymers was developed at NASA-LaRC under the JPL's task LoMMAs. The polymers are grafted elastomers that offer high strain under an applied electric field. Due to their high mechanical modulus, these elastomers offer a higher strain energy density than the previously reported result for such electrostrictive polymers as polyurethane. The dielectric, mechanical and electromechanical properties of this new electrostrictive elastomer are currently being studied as a function of temperature and frequency. Also investigated are the microstructure and mechanism of electrostriction in this grafted elastomer. X-ray diffraction and differential scanning calorimetry are used in this investigation. This new EAP demonstrated high actuation strain and high mechanical energy density combined with its designable molecular composition as well as excellent processability. An example of the bending response of a grafted polymer configured as a bimorph is shown in Figure 10.

PENN STATE UNIVERSITY

Electroactive Polymers with High Electrostrictive Strain and Elastic Power Density

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FIGURE 11: *Left* **-** The bimorph with no voltage applied to it. *Right* - The same bimorph after the voltage was turned on.

In many polymeric materials, a structure or conformational transformation is often associated with large dimensional change. However, it is still a challenge to make use of these transformations and electrically induce the transformation without much hysteresis for practical actuator applications. Recently, we found that in Poly(vinylidene fluoride-trifluoroethylene) (P(VDF-TrFE)) copolymers, a giant electrostriction (strain >5%) can be induced when the polymer is treated with properly high energy electron irradiation (Figure 11). Furthermore, the polymer has a high elastic modulus (~1 GPa) and the field-induced strain can operate at frequencies higher than 100 kHz, which result in a very high elastic power density compared with any electroactive polymers reported.

The new polymer actuators can be operated in air, vacuum, or water and in a wide temperature range. Extensive structural investigations indicate that high electron irradiation breaks up the coherence polarization domain and transforms the polymer into a nanomaterial consisting of local nanopolar regions in a

nonpolar matrix. It is the electric field induced change between non-polar and polar regions that is responsible for the giant electrostriction observed in this polymer.

SDSM&T AND MSU

Active Polymers: Properties and Applications

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Current research interests concern the use of active polymers for space applications. MSU is investigating polyvinylidene fluoride (PVDF) for active vibration control in microgravity environments. The polymer can be characterized as a light, compliant material that exhibits considerable dielectric strength, high sensitivity to mechanical loads and stable piezoelectric properties in diverse chemical environments.

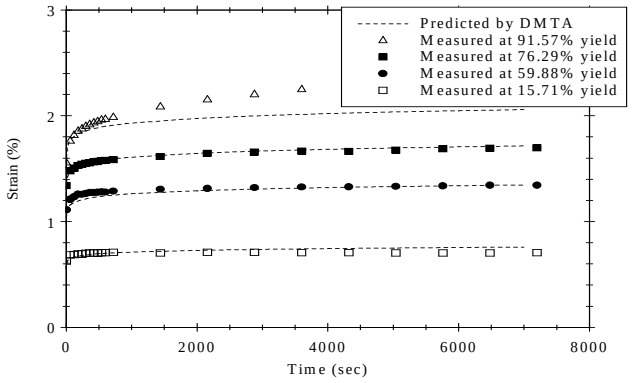

FIGURE 12: Creep of PVDF (material direction 1).

Creep tests of PVDF thin films under room temperature conditions demonstrate that linear viscoelastic theory based on Boltzmann's superposition principle accurately represents the time-dependent response of PVDF, provided that the applied stresses remain below certain limits. Beyond these limits, creep properties of PVDF must be characterized by a nonlinear viscoelastic constitutive model (Figure 12).

The Compliant Structures Laboratory at SDSM&T has shown in simulations that manipulating the boundary (rim) of an inflatable membrane reflector reduced the figure error in the inflated profile. An inflated membrane reflector was simulated using the nonlinear FEM code ABAQUS. PVDF actuators were simulated to apply radial boundary displacements (Figure 12). Table 1 shows the rms surface error for two cases of uniform radial boundary displacement after inflation: 2.54 mm and 5.08 mm, respectively. It is seen that the surface error is significantly reduced by the boundary manipulation.

Table 1. Comparison of precision metrics, with and without uniform radial boundary displacements (F=1.04).

Boundary displacement	Pressure	1/2 aperture	w0	RMS surface Error	% improve-ment
mm	kPa	mm	mm	mm	
0.0	5.17	533	64.0	1.31	--
2.54	7.72	536	64.5	1.12	14.5
5.08	10.2	538	64.8	0.886	32.4

SRI INTERNATIONAL

Electrostatically actuated EAP showing large actuation strain

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For the past seven years, SRI International has been developing an actuator technology based on the deformation of soft-rubbery dielectric materials under the influence of high electric fields. A key feature of this technology is the use of highly compliant electrodes that allow thin polymer films to expand in area as they compress in thickness. Initial work was focused on the development of artificial muscle microactuators as part of Japan's Micromachine Program, sponsored by MMC/NEDO/MITI. This effort is led by Dr. Ron Pelrine. The research team includes individuals working in the areas of physical electronics, polymer chemistry and mechanical and electrical engineering.

Silicone rubber materials (based on polydimethyl siloxane) have reliably shown the greatest strain deformation. A variety of other rubbery dielectric polymers have also shown large strains. Recently, SRI has been able to reproducibly achieve more than 100% strain in a planar direction with a stretched silicone rubber film (see Figure 13). The specific elastic energy of such materials is comparable to the best field-actuated materials, including single-crystal piezoelectrics. The good electromechanical response of these materials, as well as other characteristics such as good environmental

tolerance and long-term durability, suggest a wide-range of possible applications. SRI has made actuators in configurations such as bending beams (unimorphs and bimorphs), linear extenders, diaphragms, rolls, tubes, stacks as well as some novel configurations. Rotary and linear motors, that rectify the oscillation of linear actuator elements, have also been demonstrated.

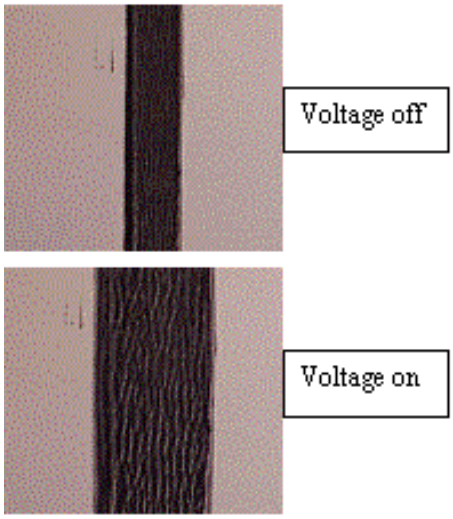

FIGURE 13 Stretched Silicone-rubber film with carbon-grease electrodes (dark area) undergoing 117% strain in the transverse direction.

These elastomeric polymer transducers present many unique challenges in design, fabrication and integration with high-voltage electronic drivers that may ultimately affect their suitability for specific applications. Applications that are under active investigation include acoustic actuators for smart skins and low profile speakers, microactuators for pumps, valves, and optics, artificial muscle actuators for biomorphic walking, flying and serpentine robots. SRI has also recently begun investigating these materials, not only as actuators, but also as electric power generators for converting human motion and other mechanical work into electricity.

UNIVERSITY OF ARIZONA

Layered hydrogels as electrically driven muscles

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Natural muscle develops a peak stress of about 300 kilopascals at a contraction of about 25%. Chemical energy in the form of ATP and calcium ions causes a linear contraction at roughly constant volume in highly aligned fibers of a combination of two polymers, actin and myosin. Even for nature, this was apparently quite difficult to develop, because essentially the same system is used across the whole animal kingdom from nematodes to humans. A synthetic muscle for robotics should at least match the stress and response time of natural muscle but should be driven electrically. In past work, applying an electric field to hydrogel polymers caused bending or a volume change, but not a simple linear contraction. By combining two polymer gels, one contractile and one acting like a passive sponge, we can achieve a linear contraction of 10% reversibly, without driving water out of the system. The active layer contracts in 3 dimensions and causes the "sponge" layer to contract with it along x and y but expand along z. As a whole the system gets narrower and thicker. This is shown in the figure. The system is far from optimized but does illustrate how a practical gel muscle could be constructed.

Ref: SPIE Proceedings 3669, (1999) pp. 236-241.
http://www.aml.arizona.edu/faculty/calvert/index.html

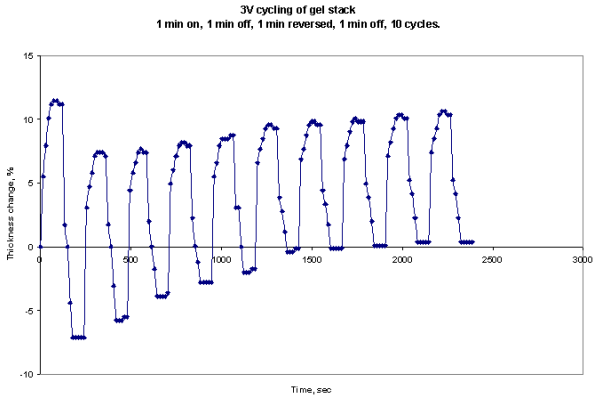

FIGURE 14: Cycling of a gel stack from +3V to 0V to -3V to 0V.

UNIVERSITY OF CALIF., SAN DIEGO (UCSD)

Electromechanical Response of Ionic Polymer-Metal Composites

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An ionic polymer-metal composite (IPMC) consisting of a thin Nafion sheet, platinum plated on both faces, undergoes large bending motion when an electric field is applied across its thickness. Conversely, a voltage is produced across its faces when it is suddenly bent. A

micromechanical model accounts for the coupled ion transport, electric field and elastic deformation to predict the response of the IPMC, qualitatively and quantitatively. First, the basic three-dimensional coupled field equations are presented, and then the results are applied to predict the response of a thin sheet of an IPMC. Central to our theory is the recognition that the interaction between an imbalanced charge density and the backbone polymer can be represented by an eigenstress field. The constitutive parameter connecting the eigenstress to the charge density is calculated directly using a simple microstructural model for Nafion. The results are applied to predict the response of samples of IPMC, and good correlation with experimental data is obtained. Experiments show that the voltage induced by a sudden imposition of a curvature, is two orders of magnitude less than that required to produce the same curvature. The theory accurately predicts this result. The theory also shows the relative effects of different counter ions, e.g., sodium versus lithium, on the response of the composite to an applied voltage or curvature.

Skeletal Muscle as a Biological Example of a Linear Electro-Active Actuator

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Skeletal muscle represents a classic biological example of a structure-function relationship. Muscle anatomy demonstrates molecular motion on the order of nm distances that is converted to macroscopic movements in skeletal muscle. Muscle anatomy provides a structural basis for understanding the basic mechanical properties of skeletal muscle namely, the length-tension and force-velocity relationships. The length-tension relationship illustrates that muscle force generation is extremely length-dependent due to the interdigitation of the contractile filaments. The force-velocity relationship is characterized by a rapid force drop in muscle with increasing shortening velocity, and a rapid rise in force when muscles are forced to lengthen. Finally, muscle architecture the number and arrangement of muscle fibers has a profound effect on the magnitude of muscle force generated and the magnitude of muscle excursion. These concepts demonstrate the elegant manner in which muscle acts as a biologically regenerating linear motor. These concepts can be used in developing artificial muscles as well as in performing surgical reconstructive procedures with various donor muscles.

UNIVERSITY OF MICHIGAN, ANN ARBOR

Organic Polymer Light-Emitting Devices and Displays

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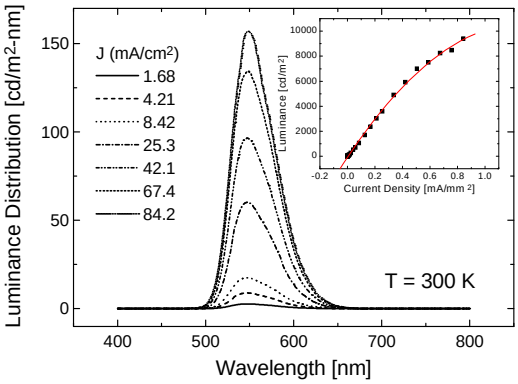

FIGURE 15: Spectral distribution of the OLED luminance under different operating current densities. The inset shows the OLED brightness versus injection current.

Through optimization of the organic polymer light-emitting device (OLED) structure and modification of the polymer's chemical structure, we have fabricated high-performance organic polymer light-emitting hetero-structure devices on both glass and flexible plastic substrates. The OLEDs fabricated on the glass substrate showed a brightness of ~10,000 cd/m^2, external quantum efficiency of 3.8%, emission efficiency of 14.5 cd/A, and luminous efficiency of 2.26 lm/W. Using a unique charge-coupled device (CCD) calibration method developed in our group, we have obtained the spectral distribution of the luminance, photon emission of the organic light-emitting device. Today we are trying to develop the active-matrix organic polymer light-emitting displays on both glass and plastic substrates. The active-matrix arrays are based on hydrogenated amorphous silicon thin-film transistor technology.

References:
He Y., et al, Appl. Phys. Lett., 74, 2265-2267, (1999).
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FEORC, VIRGINIA TECH

Muscle Actuators Fabricated by the Electrostatic Self-Assembly Process

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FIGURE 16: Muscle actuator synthesized by ESA process, working in air.

Under the NASA telerobotic task entitled LoMMAs, researchers at FEORC have successfully fabricated muscle actuators by the novel electrostatic self-assembly (ESA) process. This method allows the alternate adsorption of cationic and anionic molecules from separate water-based solutions at room temperature and pressure to form multilayered thin films with excellent uniformity at the molecular level. A conducting electrode and ultrahard protective coating technique were developed using metal nanoclusters self-assembled with polymers to produce the electrodes. Prior FEORC work has shown that such ESA thin films have electrical conductivity on the order of that of bulk metals, suggesting that the ESA process avoids the defects and impurities that typically lead to much larger thin-film resistivity. For low-mass muscles, the ability to attain such high conductivity in a very thin and very flexible electrode is a significant advantage. Several kinds of prototype MEMS devices and actuators have been designed and fabricated by optimizing the combination of the synthesis of piezoelectric thin films, electrode films and hard coatings (Figure 16). Current research is focused on determining the mechanical degradation effects on the electrodes after they are repeatedly cycled, and developing and synthesizing novel electroactive materials by the ESA process for muscle actuators.

UPCOMING EVENTS

Sept. 20-23, 1999	4th Workshop on Multifunctional & Smart Polymer Systems, Dublin, Ireland, Celine.Healy@dcu.ie
Nov. 29 to Dec. 3 1999	MRS, Boston, MA, Website: http://www.mrs.org/meetings/fall99/cfp/symposia/ff.html
March 6-7, 2000	SPIE joint Smart Materials and Structures and NDE, Newport Beach, CA., Pat Wight patw@spie.org Website: http://www.spie.org/web/meetings/calls/ss00/ss04.html

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