WorldWide ElectroActive Polymers

EAP

(Artificial Muscles) Newsletter

June 2001 **WW-EAP Newsletter** **Vol. 3, No. 1**

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

FROM THE EDITOR

Yoseph Bar-Cohen, *yosi@jpl.nasa.gov*

Over the last three years, the field of EAP has grown significantly in number of investigators and potential users that are considering applications for these materials. The EAP characteristics of inducing large displacements and the functionality that emulates biological muscles are making EAP materials highly attractive. To make these materials actuators-of-choice it is necessary to solidify the technical foundations and identify niche applications where their unique capabilities provide the necessary edge. The communication forums and archives that were established for the field including the SPIE and MRS conferences, the WW-EAP webhub, this WW-EAP Newsletter and the recent publication of the SPIE Press book entitled "Electroactive Polymers (EAP) actuators as artificial muscles" are providing a wealth of information and cooperation opportunities for this multidisciplinary field [http://ndeaa.jpl.nasa.gov/nasa-nde/lommas/eap/EAP-book_outline.htm and http://ndeaa.jpl.nasa.gov/nasa-nde/lommas/eap/EAP-web.htm].

We are continuing to be at a distance from meeting the challenge of an EAP actuated robotic arm that can win a wrestling match against human opponent. While it is a futuristic objective, significant progress has been made in all the elements that are critical to the infrastructure of this field. In parallel, at Caltech, Duke University and other neurological research facilities efforts are being made to interface signals from brains to robotic devices. This is an important capability for the potential of future implementation of EAP actuators in the human body. It may become feasible in future years to control EAP actuated artificial limbs and prosthetics directly from the human brain. Progress in this area gives hope that some day physically disabled persons will be able to function independently and appear natural using artificial prosthetics that are driven by EAP.

ABOUT THE EXPERTS

Ray Baughman and Anvar Zakhidov

Ray Baughman, who originated the concepts of both conducting polymer and carbon nanotube artificial muscles, and leads an international team that is developing the latter devices, is going to the University of Texas at Dallas (UTD) in August. He will become the Robert A. Welch Professor of Chemistry and the Director of the UTD NanoTech Institute. Ray's close colleague Anvar Zakhidov will join him there as a full Professor in the Physics Department. Other well-known nanotechnologists joining Ray and Anvar in the Nanotech Institute are

Dr. Alan Dalton of Trinity University in Dublin, Ireland, Dr. Igor Efimov of Russia from Leicester University in the U.K., Dr. Edgar Munoz of the University of Saragossa in Spain, Dr. Bog Gi Kim from Rutgers University, and Robert Morris of Morris Research. Actuators, from nanoscale to large scale, will be a key part of their continuing research, which will also include such other areas as photonic crystals and multifunctional materials for energy storage and energy harvesting. Ray's and Anvar's e-mail addresses at UTD will be baughmn@utd.edu and zakhidov@utd.edu . They can be also reached at (972) 883-2905 and (972) 883-2846, respectively.

Edwin Jager

In July, Edwin Jager from the Laboratory of Applied Physics, at Linköping universitet, Sweden will be joining the start-up company Micromuscle AB www.micromuscle.com . At his new affiliation he will be developing Polyppyrole (PPy) based (micro)actuators for biomedical applications. His new email will be edwin.jager@micromuscle.com. At Linköping universitet, he made significant contributions to the development of EAP micro-actuators based on conductive polymers including microrobots based on PPy and microactuators that could be fully controlled for manipulation of micrometer sized objects, such as cells [Science, 2000, 288, p2335-2338 and Science, 2000, 290, p1540-1545]. He obtained a doctor degree in May and his thesis is entitled "Microsystems Based on Polypyrrole Microactuators: Microrobots and Cell Clinics" [Linköping Studies in Science & Technology Dissertations No. 694]. http://www.bibl.liu.se/liupubl/disp/disp2001/tek694s.pdf.

GENERAL NEWS

The WW-EAP Webhub is continuing to be updated with information regarding the EAP activity Worldwide. This webhub is hosted at the JPL's NDEAA Technologies Website: http://ndeaa.jpl.nasa.gov

LIST OF CONTENTS

2001 SPIE EAPAD Conference

Since the first SPIE conference on EAP that was held in March 1999, the field of Electroactive Polymers has emerged from its anonymity to the spotlight of the science and engineering community.

FIGURE 1: Attendees of the SPIE's EAPAD Conference during the "EAP in Action Session".

Indicators of this growth are the number of participants and the close to 70 papers that were presented at the SPIE's EAPAD 2001 Conference that was held in March this year at Newport Beach. This conference has grown to four days from two in the first conference. The presentations covered a broad range of topics ranging from analytical modeling to application that constitute the elements of the field infrastructure. The EAPAD Conference (#4329) program is available via the Internet on the SPIE website:
http://spie.org/web/meetings/programs/ss01/confs/4329.html

The presented papers focused on issues that can help transiting EAP to practical use, including improved materials, better understanding of the principles responsible for the electromechanical behavior, analytical modeling, processing and characterization methods and considerations of various applications. To clarify the distinctions between the various EAP materials and operation principles, the Chair divided them into three groups: electronic, ionic, and molecular. The electronic ones are driven by electric forces and involve mostly movement of electrons. The ionic EAPs consist of electrodes and electrolytes and involve mobility/diffusion of cations or anions. The third group is still in infancy and it is involved with a molecular scale EAP.

Papers in this conference covered the following topics:

- Electroactive polymers (EAP) and non-electro active-polymers (NEAP)
- Models, analysis and simulation of EAP behavior
- Biological muscles as a potential model for EAP actuators
- EAP as artificial muscles, actuators and sensors
- Methods of testing and characterization of EAP properties and performance
- Support technologies including control, design and fabrication processes
- Applications of EAP actuators

The presented results are showing improved understanding of the electromechanical mechanisms and better methods of addressing the challenges to the processing and applications of these materials. Researchers are developing analytical and theoretical models to describe the electro-chemical and -mechanical processes, non-linear behavior as well as methodologies of design and control. EAP materials, including IPMC, dielectric and electrostrictive types, were reported to exhibit much improved response. Also, the use of composite electrostrictive polymers was shown to have promise in reducing the needed high actuation voltage. New fabrication methods as well as test and characterization techniques have also emerged. Further, applications to biologically inspired robots, entertainment, animatronics, and many other fields are being explored with encouraging results.

The Conference Keynote Speaker was Richard Andersen, Caltech, (see Figure 2) and his presentation was entitled "Developing a neural prosthesis for reaching." In his presentation, he described the efforts of neurologists at Caltech and other universities to interface the brain to machines translating thoughts into action. Interfacing the brain and robotics can potentially allow using robotic devices that are controlled directly by human brain. Progress in this area can potentially allow disabled persons to perform normal functions using artificial limbs that may be driven by EAP.

FIGURE 2: The Keynote Speaker, Richard Andersen, Caltech, described the efforts to interface the brain to machines.

During the EAP-in-Action Session, the attendees were given opportunity to see four demonstrations of EAP actuators and devices. This Session is a forum of interaction between the technology developers and potential users as well as a "hands-on" experience with this emerging technology.

FIGURE 3: Ron Pelrine, SRI International, presenting applications of Dielectric Elastomer EAP. A speakerphone was demonstrated playing the Beethoven's 5th Symphony.

FIGURE 4: Giovanni Pioggia, University of Pisa, showing the Android head that is offered as a platform for EAP actuators.

The presentations in this session included:

- **"Dielectric Elastomers**: Stretching the Capabilities of Actuators, Generators and Sensors" (see Figure 3) -- R. Kornbluh, R. Pelrine, Q. Pei, J.N Heim, R. Heydt, J. Eckerle, and S. Oh, SRI International - This presentation included several devices that are driven by Dielectric EAP including a speaker that was used to play the 5th Symphony of Beethoven at a very high fidelity.
- **"Dielectric elastomer** actuator" -- P. Sommer-Larsen, Risoe National Lab., Denmark - An actuator was shown to lift a large mass.
- "Soft micromanipulation device with multiple-DoF using **IPMC actuators"** -- S. Tadokoro and his students, Kobe University, Japan – A miniature IPMC actuated manipulator was shown.
- "Android with facial expressions - a **platform** for EAP actuators" (see Figure 4) -- Giovanni Pioggia, University of Pisa, Italy – A robotic head controlled wirelessly was shown to make facial expressions and eyes movement.

Also, an Open Discussion Session was held to debut the status of the field of EAP, where the conference Chair, Cochair, and the invited speakers served as the discussion panelists. Each of the panelists (see Figure 5) gave a short presentation of his views and the attendees expressed thoughts and comments. This session was intended to stimulate ideas and thought with no attempt to reach a consensus. The general views have been that the field is moving in the right direction but we still have a way to go. The panel Moderator was the Conference Chair: Yoseph Bar-Cohen, JPL, and the panelist included: Danilo de Rossi, Univ. degli Studi di Pisa (Italy); Siavouche Nemat-Nasser, Univ. of California/San Diego; Ron Pelrine, SRI International; Satoshi Tadokoro, Kobe Univ. (Japan); Gordon G. Wallace, Univ. of Wollongong (Australia); Steven G. Wax, DARPA; Qiming Zhang, The Pennsylvania State Univ. The topics that were discussed at this session included:

- Do we know all the mechanisms that can make polymers mechanically electroactive?
  - Are there more than electronic and ionic categories?

FIGURE 5: The panelist at the Open Discussion Session. From right to left: Steve Wax, DARPA; Gordon Wallace, Wollongong U., Australia; Ron Pelrine, SRI International; Sia Nemat-Nasser, UC San Diego; Danilo de Rossi, U. of Pisa, Italy; and Satoshi Tadokoro, Kobe U., Japan.

- What are the challenges to the performance enhancement?

- Biomaterials: Do cultured biological muscles pose potential competition to EAP?
- EAP properties and measurement methods - are we ready to standardize the test methods?
- Are EAP scalable to extreme sizes, i.e., nanotechnology and/or very large sizes?
- Are there niche applications currently underway?
- Are EAP actuators-of-choice already?

Overall this conference had the largest number of papers and with the most significant growth over prior years. The conference was well attended by leading world experts in the EAP field including members of academia, industry, and government agencies from the USA and overseas.

Call for Papers -- EAPAD 2002

The 4th EAPAD conference will be held at San Diego, CA from 17 to 21 March 2002. The call for abstracts is available on:
http://spie.org/conferences/calls/02/ss/confs/ss04.html

2001 MRS Fall Meeting

During the upcoming 2001 Fall Meeting, MRS is including a Symposium on EAP having a designation EE. This Symposium will be held in Boston, Nov. 26-30, 2001, with the objective of providing a forum for the EAP researchers to exchange information, stimulate discussions and present the recent advances. The organizers are Siegfried Bauer (Johannes-Kepler Universitaet Linz, Austria), Yoseph Bar-Cohen (JPL), Eiichi Fukada (Koboyasi Institute of Physical Research, Japan), and Qiming M. Zhang (Penn State University). The Invited Speakers are: F. Bauer (ISL, France), R. Fleming (Monash U., Australia), T. Furukawa (SU Tokyo, Japan), H. Kodama (Rion Co., Japan), K. Ikezaki (Keio U., Japan), F. Kremer (U Leipzig, Germany), J. Lekkala (VTT, Finland), M. Marsella (UC Riverside), Geoff Spinks (Australia), Danilo de Rossi (Italy), J. Su (NASA), Y. Tajitsu (Yamagata, Japan), K. E. Wise (USA). For more information you can contact Qiming M. Zhang qxz1@psu.edu or visit
http://www.mrs.org/meetings/fall2001/

Call for Papers ACTUATOR 2002

ACTUATOR 2002, *8th International Conference on New Actuators* and *2nd International Exhibition on Smart Actuators and Drive Systems*, will take place on 10 - 12 June 2002, in Bremen, Germany. For the first time, there will be a special session on EAP actuators. This session will be chaired by Roy Kornbluh, SRI international, and Peter Sommer-Larsen, Risø National Laboratory.

Abstracts for conference contributions (oral or poster presentation) are requested by 30 November 2001, preferably by e-mail to the organiser. They should be in English, must not exceed 500 words, and give the name(s) of author(s) and institution(s). Please underline the name of the author dedicated for presentation and indicate the preferred kind of presentation. The organizer of this conference is Hubert Borgmann, MESSE BREMEN GMBH, 28209 Bremen, Germany, Phone: (+49 421) 35 05 347, Fax: (+49 421) 35 05 340, email actuator@messe-bremen.de Website:
www.actuator.de

TRANSDUCING Materials & Devices 2002 Conf.

A conference that is seeking to cover all the transducing materials and devices combinations has been initiated. These materials and devices have a growing importance to many fields of technology. To name few one can list actuators, artificial muscles, sensors, displays, and many others. This Transducing Materials & Devices Conference will be held in Frankfurt, Germany from June 17 to 21, 2002. This will be the first SPIE Conference on this subject and it will be held as part of the Optatech 2002 Symposium, Photonic Systems Europe. The coordinator of this SPIE Symposium is Terry Montonye, terry@SPIE.org and the Chair for this specific conference is Yoseph Bar-Cohen, yosi@jpl.nasa.gov An organization committee and the call for papers are currently being prepared and should be ready at the end of July.

Establishment of EAP Platforms

Recently, in an effort to promote the development of effective EAP actuators, the Editor solicited the establishment of two biologically inspired platforms. These platforms consist of an Android Head (Figure 6) and a Robotic Hand (Figure 7). The objective of these platforms is to provide testbeds for new EAP to demonstrate their capability and viability. Such development can strongly impact the future of biomimetic technology that includes robotics, animatronics, and toys. The Android Head can make facial expressions and the robotic hand has activatable joints [videos are available on http://ndeaa.jpl.nasa.gov/nasa-nde/lommas/eap/EAP-web.htm].

FIGURE 6: An Android head making facial expressions [Courtesy of Giovanni Pioggia – U. of Pisa, Italy/JPL (photographed at JPL)]

At present, conventional electric motors are producing the 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 and imitated by the android if one uses a digital camcorder to form motion capture sequences. 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 is equipped with tandems and sensors for the operation of the various joints mimicking a human hand. Conventional motors currently drive the index finger of this hand, which establishes a baseline. These motors would be substituted by EAP when such materials are developed as effective actuators.

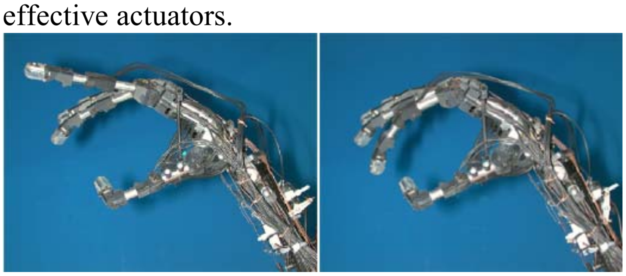


FIGURE 7: Robotic hand as a platform for EAP demonstration [This Robotic Hand is a courtesy of Graham Whiteley, Sheffield Hallam University, UK.; The actuators installed by Giovanni Pioggia – U. of Pisa, Italy/JPL (Photographed at JPL)]

WW-EAP Fabrication Recipes

Progress in EAP has been hampered by the unavailability of commercial EAP materials and actuators. Generally, one who seeks to explore the technology can contact those who are making the materials and ask for samples or seek cooperation. The Editor of this Newsletter can help foster such contacts. Another alternative is to produce the materials yourself and to assist you the Editor prepared a website called "WW-EAP Fabrication Recipes" The website was prepared thanks to inputs from several leading EAP researchers who shared their material preparation procedure. The URL address for this website is http://ndeaa.jpl.nasa.gov/nasa-nde/lommas/eap/EAP-recipe.htm Recently, this website was updated with input on Carbon Nanotubes that prepared by Giovanni Vozzi, University of Pisa, Italy. The homepage now contains preparation procedures for the following EAP materials:

Ionic EAP

- IPMC
- Conductive polymer
- Gel EAP
- Carbon Nanotubes

Electronic EAP

- Dielectric EAP

Non-EAP

- PH activated polymers

Recent EAP Publications in *Nature* and *Science*

Liquid-Crystal EAP - The need to activate the electronic EAP materials by a lower voltage was recently addressed in an article that was published by F. Kremer and W. Lehmann in *Nature*, **410**, 447, 2001. These two researchers from Germany reported there development of ferroelectric liquid crystal elastomeric EAP film that shrinks 4% in a 1.5 MV/mm electric field. Such displacement was previously achieved using copolymers but it required two orders of magnitude higher field. These researchers and their colleagues hooked chiral liquid crystal molecules and molecules that were derived with cross-linkable tails in a 9:1 ratio on a polysiloxane backbone. The produced comb-like assembly was stacked as a head-to-tail self-organized layered structure. Under electric field activation the liquid-crystal molecules tilt sideways and shrink the material in a film form. The reported material is suggested to be suitable for use in Nano-machines as actuators, transducers and related elements.

EAP ADVANCEMENTS

CUNY, Boston University Marine Program

Why use bones if you have the muscles?

Frank W. Grasso fgrasso@biomimetics.mbl.edu

EAP artificial muscles may find application in biomimetic robots aimed at modeling a special class of biological systems. They may be even better suited to this application than traditional actuators. Animals, like squid, cuttlefish and octopus achieve respectable dexterity and force generation as well as virtuoso manipulation skills without the benefit of a bony skeleton or hard external shell. Certain appendages like the tongues of mammals, reptiles and amphibians and the trunks of elephants fall into this category as well. These are examples of muscular hydrostats [Kier, 1985; Smith and Kier, 1989], systems in which the muscle provides both the mechanical support for position control as well as the force for motion.

Nature achieved this dual role for muscle by evolving architectures of short, interwoven muscle bundles throughout the structure. The interwoven bundles are arranged at various orientations of mechanical advantage and alternately pull with and against one another to produce the desired degree of tension, rigidity and flexibility at the points where it is needed. The result is what roboticists refer to as a hyper-redundant system: arms for locomotion (octopus), fins for swimming (cuttlefish) and limbs for manipulation (trunks of elephants, tentacles of squid, arms of cuttlefish, and the tongues of frogs) with virtually infinite degrees of freedom.

FIGURE 8: Cuttlefish achieve locomotion with their fins, fast ballistic prey capture with their tentacles, and dexterous manipulation of objects with their arms without the benefit of a hard skeleton. Composed of muscle and connective tissue, MH systems fulfill the structural role played by skeletons in vertebrates in addition to generating force (Photo credit to Roger Hanlon).

The CATSIRM (Cephalopod Arms, Tentacles and Senses as Inspiration for Robotic Manipulators, May 3-9 2001, AAAS Jonsson Center in Woods Hole) workshop was held to explore these possibilities. Sponsored by DARPA-ATO and organized by Roger T. Hanlon, William M. Kier and Frank W. Grasso this workshop brought together biologists, neuroscientists, roboticists and actuator engineers (including M. Shahinpoor and Q. Zhang) to evaluate the pitfalls and prospects for developing artificial MH systems. The consensus of the workshop participants was that traditional actuator technologies are not practical for implementing the biological understanding of MH systems into practical machines. Placing a motor at each traditional joint on the arm imposes serious weight and space limitations on the number of joints that can be realized. While remote motors coupled to traditional joints through tendons offer potential exploration of control strategies, they still cannot approach the degrees of freedom in biological MH systems.

By more closely emulating real muscles, EAP artificial muscle offers a way around the space and weight problems. The strains achieved by EAPs however seem too low at present to emulate those realized in biological EAP systems. But maybe the realization of the first artificial MH system awaits the appropriate combination biologically inspired geometry and an EAP muscle ensemble with just enough pull?

REFERENCES

Kier, W. M. 1985. Toungues, tentacles and trunks: the biomechanics of movement in muscular-hydrostats. Zoological Journal of the Linnean Society 83: 307-324.

Smith, K. K. and W. M. Kier 1989. Trunks, toungues and tentacles: moving with skeletons of muscle. American Scientist 77: 28-35.

Jet Propulsion Laboratory (JPL)

EAP CHARACTERIZATION – IPMC OPERATION UNDER LOAD

Y. Bar-Cohen, yosi@jpl.nasa.gov, X. Bao, V. Olazabal, JPL, K. Bhattacharya and Yu Xiao, Caltech

Ionic Polymer-Metal Composite (IPMC) as electroactive polymers (EAP) was the subject of research and development since 1992 [Nemat-Nasser and Thomas, 2001]. The required low activation voltage and the large bending led to the considerations of various potential applications. However, before the benefits of IPMC can be effectively exploited for practical use, the electromechanical behavior must be properly quantified [Sherrit and Bar-Cohen, 2001]. An experimental setup was developed for data acquisition from IPMC strips subjected to various tip mass levels. In parallel, an analytical model was developed to predict the material response [*Bhattacharya, et al, 2001]*. Using the analytical model and an inversion algorithm the modulus, and relaxation time were determined.

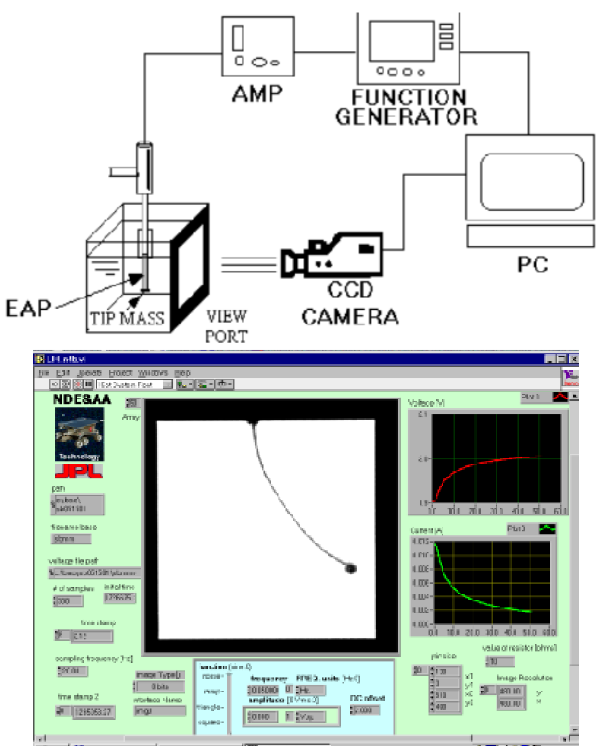


FIGURE 9: Displacement measurement setup and the display of the activated IPMC with tip mass.

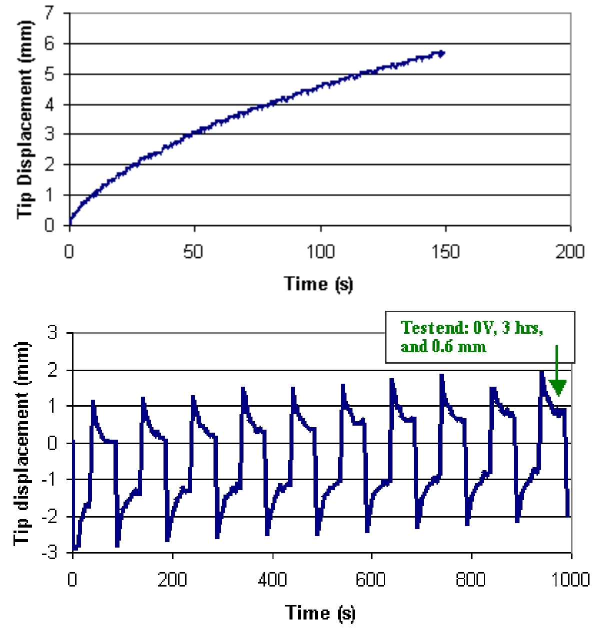


FIGURE 10: Displacement of IPMC as a function of time under 1-V for samples made of the following backbones: Top -Flemion (ONRI, Japan); Bottom – Nafion (ERI)

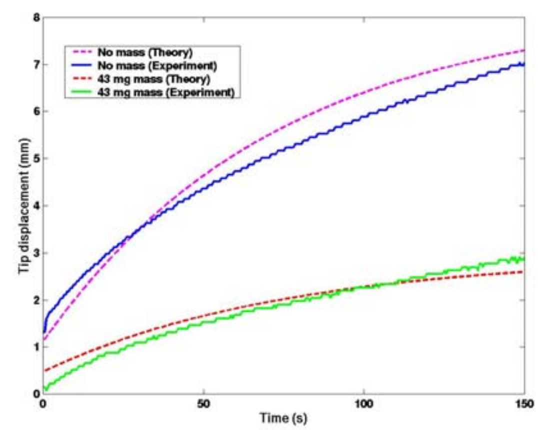


FIGURE 11: Experimental and analytical data for the Flemion base IPMC samples with and without tip mass.

A programmable setup was developed to acquire the displacement and curvature of IPMC as a function of the electrical signal characteristics. Sample strips were immersed in water to minimize the effect of moisture content and were tested with and without tip mass. In order to avoid hydrolysis the samples were subjected to 1-V square wave with either positive or negative polarity. A multi-scale model was developed that showed satisfactory results for tetra-n-butylammonium^{+} cations/ Flemion IPMC, which responds slowly and monotonically without relaxation. This model starts at the mesoscale level with three fully coupled partial differential equations in cation concentration, electric potential and elasticity. Solution in the strip geometry leads to a macroscopic ordinary differential equation whose solution fits the observed behavior very well. Deviation from the model was observed when the material shows relaxation, as in the case of Li^{+} cations/Nafion. This type of IPMC responds with a quick bending that in fractions of a second starts relaxing. Address this deviation and the material behavior history dependence would require further studies.

REFERENCE

Bhattacharya K., J. Li and Xiao Yu, "Electromechanical Models for Optimal Design and Effective Behavior of Electroactive Polymers," Topic 4, Ch. 12, "Electroactive Polymer (EAP) Actuators as Artificial Muscles - Reality, Potential and Challenges," Y. Bar-Cohen (Ed.), SPIE Press, (2001), pp. 309-330.

Nemat-Nasser S. and C. W. Thomas, "Ionomeric Polymer-Metal Composites," ibid, Topic 3.2, Ch. 6, pp. 139-191.

Sherrit S. and Y. Bar-Cohen, "Methods of Testing and Characterization," ibid, Topic 6, Ch. 15, pp. 405-453.

NEW APPLICATIONS OF COLD HIBERNATED ELASTIC MEMORY (CHEM) SELF-DEPLOYABLE STRUCTURES

Witold Sokolowski,
Witold.M.Sokolowski@jpl.nasa.gov

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 and are using the foam's elastic recovery plus their shape memory to erect a structure. In practice, the CHEM foams are compacted to small volume 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.

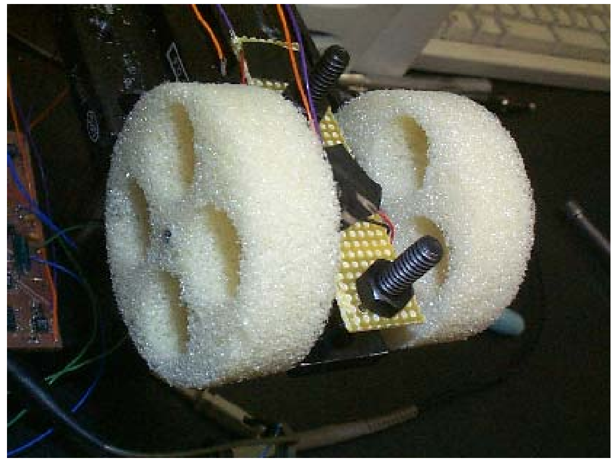


FIGURE 12: CHEM Nano-rover Wheels.

The CHEM foam materials are under development by the Jet Propulsion Laboratory (JPL) and Mitsubishi Heavy Industries (MHI). Currently, the CHEM foam concept is well formulated, with clear space and commercial applications. Previous experimental results were very encouraging; the accumulated data indicate that the CHEM foam concept performs robustly in the Earth environment as well as in space.

In addition, the test/evaluation results and preliminary analyses show that the CHEM foam concept is a viable way to provide a lightweight, compressible structure that can recover its original shape after long-term compressed storage. One example is the demonstration of CHEM wheels developed for the sub-scale nano-rover (see Figure 12). Other potential applications, such as a horn antenna, camera mast, and a sensor delivery system, were studied under various programs at JPL. Further, the researchers anticipate many applications to such areas as recreation, toys, automotive and biomedical.

Penn State University

HIGH ELECTROSTRICTIVE PVDF BASED TERPOLYMERS

Qiming M. Zhang, qxz1@psu.edu

The successful development involving the use of high-energy electron irradiated P(VDF-TrFE) copolymers led to the high electrostrictive strain (~5%) with elastic energy density ~0.8 J/cm^3. Recently, researchers at Penn State University eliminated the need for irradiation with their development of PVDF based terpolymers which exhibit strain near 5% having elastic energy density that is more than 1.1 J/cm^3, and it is better than the irradiated copolymers. This elimination of the need for irradiation reduces the cost and is markedly simplifying the manufacturing process. The advantages of this class of polymers are its high modulus (~ 1 GPa) and high frequency capability (>100 kHz). In addition to the high electromechanical responses, the terpolymers also possess high room temperature dielectric constant (~ 60), which is more 10 times higher than any other polymeric materials.

University of Illinois, Urbana-Champaign (UIUC)

SIMULATION OF pH SENSITIVE HYDROGELS

Sudipto K. De and N. R. Aluru aluru@uiuc.edu

Ionic polymer gels are composed of a network of cross-linked polymer chains and an internal solution that surrounds the chain. The polymer chains have ionizable groups (fixed charges) capable of dissociating in the presence of a solvent. These gels are sensitive to the outer solution pH and salt concentration. Changes in these conditions can result in large changes in gel size [4, 5], making it possible to use them as both actuators and sensors.

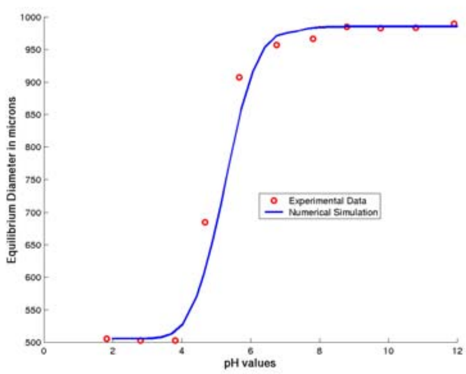


FIGURE 13: Equilibrium swelling of a 400 μm hydrogel

The equilibrium model predicts the change in gel size when it is placed in a pH solution. To preserve electro-neutrality inside the gel, the fixed charges draw ions from outside and an ionic concentration difference is created, giving rise to an osmotic pressure. This causes inflow or outflow of liquid from the gel and hence the gel size changes. Equilibrium is established as a result of the restoring force generated by the crosslinks in the polymer network. The equilibrium process has been modeled using the steady-state Nerst-Planck equation [2], the Poisson equation and the mechanical equilibrium equation. Figure 13 shows the simulations along with the experimental data for a 400 μm hydrogel [1].

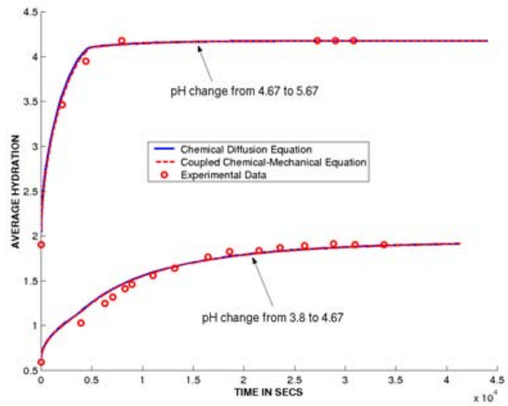


FIGURE 14: Swelling kinetics of a 400 μm hydrogel for pH changes of 3.8 to 4.67 and 4.67 to 5.67.

The kinetics of the swelling process is modeled following the model presented in [3]. A coupled Chemical-Mechanical equation has been developed [4]. The presence of a buffer in the solution significantly improves the swelling process. We observe that the hydrogel kinetics is a diffusion limited process and the Chemical equation alone can describe the swelling kinetics quite accurately. Figure 14 shows the simulations along with the experimental data for the swelling kinetics of a 400 μm hydrogel for two different pH changes [1].

REFERENCES:

[1] Beebe DJ, et. al., Nature, Vol 404, April 2000.
[2] Szymczyk, et. al., J. of Membrane Sc.,Vol 161, pp 275-285, 1999.
[3] Grimshaw PE, PhD Thesis, MIT, 1990.
[4] Ohs RR, Masters Thesis, UIUC, 2001.
[5] Chu Y, et. al., J. of Appl. Pol. Sc., 70, pp 2161-2176, 1995.

Virginia Tech

IPMC ELECTROMECHANICAL COUPLING

Donald J. Leo, donleo@vt.edu
http://filebox.vt.edu/users/donleo/

New results in electromechanical coupling and control of ionic polymer devices have been obtained at the Virginia Tech Center for Intelligent Material

Systems and Structures. Several experiments have been performed on small (10-30 mm x 5 mm x 0.2 mm) cantilevered samples of metal-coated Nafion to understand the electromechanical transduction properties of these devices. Feedback control experiments have also been performed to demonstrate the ability to increase the bandwidth of cantilevered actuators.

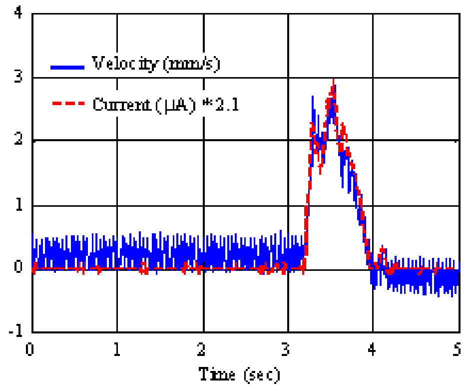


FIGURE 15: Velocity and current measurement demonstrating the proportionality of the two variables.

ELECTROMECHANICAL COUPLING BETWEEN CURRENT AND VELOCITY (K. Newbury / D. Leo)

Experiments on cantilevered samples of gold-electroded ionic polymer material have demonstrated that there is a direct electromechanical coupling between electrical current and material velocity. Figure 15 is a comparison between the short-circuit current of the sample and the velocity induced by point load at the tip. The results demonstrate that the two measurements are proportional to one another for the amplitude and duration of the present experiment. This result is being used to develop new models of electromechanical transduction and bidirectional energy transfer [1].

TEN-FOLD INCREASE IN ACTUATION BANDWIDTH USING FEEDBACK CONTROL (K. Mallavarapu / D. Leo)

Experiments demonstrated that a tenfold increase in actuation bandwidth is possible using feedback control. Figure 16 is a comparison of the open-loop and closed-loop response of a cantilevered sample of ionic polymer material to a step change in the electric field. Feedback control of the sample eliminates the large overshoot associated with the material response and reduces the time it takes to reach steady-state from 20 seconds to between 1-2 seconds [2, 3].

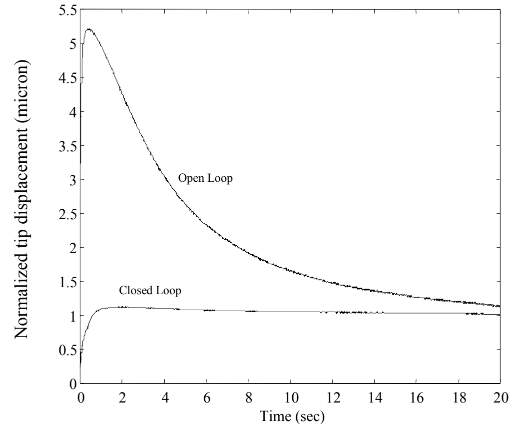


FIGURE 16: Comparison of open- and closed-loop step response for an ionic polymer actuator.

NICKEL-COATED NAFION SAMPLES FABRICATED AND TESTED (M. Bennett / D. Leo)

Samples of nickel-coated Nafion were fabricated using an electroless deposition process. Forces on the order of 1-5 mN were measured for a 3-volt step input (see Figure 17). Work is currently focused on improving the longevity and repeatability of the samples.

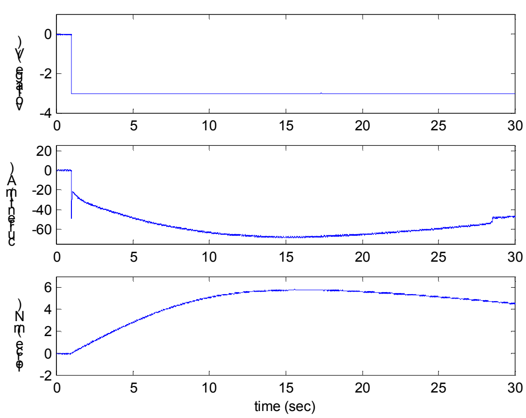


FIGURE 17: Measured voltage (top), current (middle), and blocked force (bottom) for a nickel-coated ionic polymer actuator.

Acknowledgement: The group would like to thank M. Shahinpoor and K. Kim of the University of New Mexico for providing the gold-electroded samples used in the first two studies.

REFERENCES:

1. Newbury, K.M., Leo, D.J., 2001, ‘ Mechanical work and electromechanical coupling in ionic

polymer materials,' ASME Adaptive Structures and Materials Symposium, submitted.

2. Mallavarapu, K., Newbury, K.M., Leo, D.J., 2001, "Feedback control of the bending response of ionic polymer metal composite actuators," SPIE Paper No. 4329-40.
3. Mallavarapu, K., Leo, D.J., 2001, 'Feedback control of the resonant response of ionic polymer actuators,' ASME Adaptive Structures and Materials Symposium, submitted.

DESIRED EAP APPLICATIONS

The field of EAP has enormous potential to many areas including almost any aspect of human life. While some ideas may still be science fiction it is important to scope the requirements to the level that current materials can address. The objective of this section is to help accelerate the progress towards practical applications by providing those who are seeking to use such materials a forum to express their need directly to the EAP material developers. Interchange among those who are expressing the need and the material developers is highly welcome and feedback as well as success stories submitted to this Newsletter would be greatly appreciated.

EAP Technologies for Gossamer Spacecraft

Chris Jenkins, cjenkins@taz.sdsmt.edu

A research project is underway to investigate incorporation of EAP technology into ultra-low mass ("gossamer") spacecraft. Gossamer spacecraft (GS) are of interest for a variety of space missions, for example where either very large or very small spacecraft are required. In most practical cases today, ultra-low mass is achieved through use of thin film polymers and polymer-matrix composites.

Under sponsorship from NASA, C. Jenkins (South Dakota School of Mines and Technology), A. Vinogradov (Montana State University), and Y. Bar-Cohen and M. Salama (JPL) are researching method to incorporate active polymer elements into the seams and elsewhere in GS, in order to facilitate on-orbit deployment and precision shape control. A wide variety of materials, configurations, and modeling approaches are being investigated.

The research team is interested in contacting others who may be working in a similar area, or who have concepts, materials, or tools they feel might make an impact on this work. For further information, interested parties may contact Chris Jenkins (cjenkins@taz.sdsmt.edu) or Yoseph Bar-Cohen (yosi@jpl.nasa.gov).

Micro-Actuator Survey

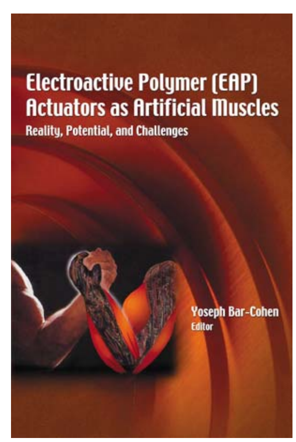
Hans Christian Petzold, petzold@isit.fhg.de

CCMicro, the Competence Center for Microactuators funded by the EU under the Europractice programme, is compiling a survey of literature, lectures and courses on micro-actuators. Everybody who is working on related topics is strongly encouraged to contribute to this survey by completing a form, to be downloaded from http://www.cmf.rl.ac.uk/CCMicro/Survey.doc and returning it to petzold@isit.fhg.de . Results will be published on the CCMicro website.

BOOKS & PUBLICATIONS

Electroactive Polymer (EAP) Actuators as Artificial Muscles

ISBN 0-8194-4054-X, SPIE Press – Editor: Y. Bar-Cohen



SPIE Press published this comprehensive book on EAP in March this year. This book reviews the state-of-the-art of the field of Electroactive Polymers (EAP), so-called Artificial Muscles. In writing this book, efforts were made to cover the field of EAP from all its key aspects, i.e., its full infrastructure, including the available materials, analytical models, processing techniques, characterization methods and applications that are being investigated. This book is intended to serve as a reference book, technology users guide, and tutorial resource, as well as create a vision for the future direction of this field. The book can be viewed on:

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

For information about purchasing the book you can contact SPIE by calling (360)-676-3290, or e-mail to bookorders@spie.org or visit the SPIE site http://www.spie.org/bookstore

Organic Electronic Materials

ISBN 3-540-66721-0 Farchioni/Grosso (Editors)

Studies on the electronic properties of conjugated polymers and low molecular weight organic solids have been of increasing interest in recent years. This book is organized into two parts dedicated to these two classes of materials. For each part a general introductory review provides background knowledge of the language and of the main points required for understanding the book's contents. The reviews that follow provide a more complete understanding of the underlying physics of the materials through discussion of the interconnected topics. Theoretical concepts, models and methods are overviewed; this is used to support the explanation of the physical and chemical properties of these materials. The presentation of selected aspects of experimental research greatly contributes to the basic understanding of organic electronic materials.

For information: Adelheid Duhm (Ms.) Physics Editorial, Springer Verlag GmbH & Co.KG Tiergartenstrasse 17 69121 Heidelberg, Germany Tel. +49-6221-487-584, Fax +49-6221-584-688
http://www.springer.de/
http://www.springer.de/phys/

AVAILABLE POSITIONS

Several postdoc positions are posted on
http://ndeaa.jpl.nasa.gov/nasa-nde/lommas/eap/Postdoc-Positions.htm

Jet Propulsion Laboratory (JPL)

Caltech Postdoctoral Scholar Position at the JPL: Electromechanical Studies of Electroactive Materials

The California Institute of Technology (Caltech) Postdoctoral Scholars Program at the Jet Propulsion Laboratory (JPL) is inviting applicants to apply for a position at the JPL's NDEAA Technologies in the area of electroactive actuators and devices. The research activity will include electromechanical studies towards the development of mechanisms for operation in space. An ultrasonic drill that is actuated by piezoelectric wafers is one of the mechanisms that are being explored. A study is underway seeking to model such mechanism towards optimization of their operation. Experimental methods are being developed to corroborate the model and design effective planetary devices.

Applicants should have a recent Ph.D. in mechanical engineering, physics, electronic engineering or a related field. Appointment is contingent upon evidence of completion of the Ph.D. degree. Annual starting salary for a recent Ph.D. is approximately $42,000 and can vary according to the applicant's qualifications. Postdoctoral Scholars positions are awarded initially for a one-year period. Appointments may be renewed in one-year increments for a maximum of two additional years.

Please send curriculum vitae, bibliography, statement of research interest and a list of three references to the address listed below. The California Institute of Technology (Caltech) Postdoctoral Scholars Program and the Jet Propulsion Laboratory (JPL) are Equal Opportunity/Affirmative Action employers. Women, minorities, veterans and disabled persons are encouraged to apply.

Yoseph Bar-Cohen, Jet Propulsion Laboratory (82-105), 4800 Oak Grove Dr., Pasadena, CA 91109-8099, e-mail: yosi@jpl.nasa.gov Website: http://ndeaa.jpl.nasa.gov/

University of Illinois at Urbana-Champaign (UIUC)

A postdoctoral position is available, to start on or before September 1, 2001, in the Beckman Institute for Advanced Science and Technology at the University of Illinois at Urbana-Champaign. The candidate will be expected to develop mathematical models and computer-aided design tools for pH and electrically responsive hydrogels. A strong background in computational methods as well as some background in polymer gels is required. Interaction and close collaboration with researchers working on fabrication and experimental aspects of hydrogels is expected. The position is for one year, but can be renewed for one or two more years based on satisfactory progress. Interested candidates should contact Prof. Aluru with a copy of vita and names of 3 references:

N. R. Aluru, 3265 Beckman Institute, MC-251
405 N Mathews Avenue, Urbana, IL 61801
e-mail: aluru@uiuc.edu
http://www.staff.uiuc.edu/~aluru

UPCOMING EVENTS

Nov. 11-16, 2001	Adaptive Structures and Material Systems Symposium, NY, NY, J. Main, johnmain@engr.uky.edu
Nov. 26-30, 2001	Symposium EE on EAP, MRS Fall Meeting, Boston, MA, Website: http://www.mrs.org/meetings/fall2001/
Dec. 12-14, 2001	International Conf. on Smart Technology Demonstrators & Devices, Edinburgh, UK, G. R. Tomlinson, g.Tomlinson@sheffield.ac.uk
Dec. 13-14, 2001	International Conf. on EAP, organized by AIST, Japan K. Asaka, asaka-kinji@aist.go.jp
March 18-22, 2002	SPIE joint Smart Materials and Structures and NDE, San Diego, CA., Pat Wight patw@spie.org Website: http://spie.org/conferences/calls/02/ss/confs/ss04.html
March 17-21, 2002	Space 2002 and Robotics 2002 Albuquerque, New Mexico. S. Johnson StWJohnson@aol.com
June 10-12, 2002	ACTUATOR 2002, Messe Bremen GMBH, Germany. H. Borgmann, actuator@messe-bremen.de Website: http://www.actuator.de
June 17-21, 2002	Transducing Materials & Devices, part of Optatech 2002, Photonic Systems Europe, Frankfurt, Germany, SPIE, Y. Bar-Cohen, yosi@jpl.nasa.gov
June 23-28, 2002	14th U.S. National Congress “Soft Actuators and Sensors,” Virginia Tech, S. Nemat-Nasser, www.esm.vt.edu/usncam14/
Dec. 9-11, 2002	Biomimetics and Artificial Muscles, Albuquerque, NM, M. Shahinpoor shah@unm.edu

WorldWide Electroactive Polymers (EAP) Newsletter

EDITOR: Yoseph Bar-Cohen, JPL, http://ndeaa.jpl.nasa.gov

All communications should be addressed to:

Dr. Y. Bar-Cohen, JPL, M.S. 82-105, 4800 Oak Grove Dr., Pasadena, CA 91109-8099
Phone: (818)-354-2610, Fax: (818)-393-3254 or E-mail: yosi@jpl.nasa.gov