WorldWide ElectroActive Polymers

EAP

(Artificial Muscles) Newsletter

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

FROM THE EDITOR

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

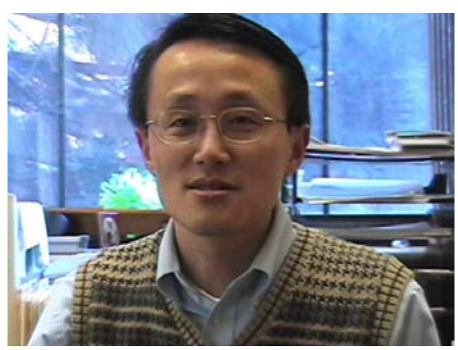
As this 6^{th} issue of the WW-EAP Newsletter is being published it is satisfactory to see the progress that has been made in the field of EAP since its emergence from its anonymity in 1999. The ability of these materials to be induced with a large displacement and the functional emulation of biological muscles are continuing to make EAP highly attractive. It is great to see that increasing number of investigators and potential users are considering applications for these materials.

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.

To turn these materials into the actuators-of-choice it is necessary to solidify its technical foundations, i.e., the infrastructure, and identify niche applications where unique capabilities of EAP would provide the necessary edge. The availability of forums and archives for communication and collaboration, including the SPIE and MRS conferences, the WW-EAP webhub, this WW-EAP Newsletter and the recent published SPIE Press book entitled "Electroactive Polymers (EAP) actuators as artificial muscles", are providing the needed information and cooperation opportunities supporting this multidisciplinary field. However, we are continuing to be at a distance from meeting the challenge of to making an EAP actuated robotic arm that can win an arm wrestling match against human opponent. Even though it is a futuristic objective, significant progress has been made in all the elements that are critical to the field infrastructure. While researchers and engineers are facing the challenges to the implementation of EAP it would be productive to consider combinations of EAP and other materials as well as finding applications where properties can be traded. A trended toward this direction can be seen in inputs that are included in this issue of the WW-EAP as well as in presentations that will be made in the upcoming SPIE's EAPAD Conference.

ABOUT THE EXPERTS

Kwang J. Kim



In August, Kwang J. Kim moved from Environmental Robots Inc. (ERI), Albuquerque NM to the University of Nevada-Reno (UNR) where he serves as the Interim Director of Nevada Ventures Nanoscience Program (NVNP) and an Assistant Professor of Mechanical Engineering Department. At UNR, he has recently established the Active Materials and Processing Laboratory (AMPL). At AMPL, he is continuing his research and development in the field of EAP where he has now a fully equipped laboratory for nanomaterials processing/related devices and characterization (see input in this issue). His teaching and research interests are broad based, but mainly in Artificial Muscles/Smart Materials, Nano-technology, and Thermal Sciences/Energy Systems. His new e-mail address is: kwangkim@unr.edu

Jiangyu Li

In August, Jiangyu Li joined the Department of Engineering Mechanics, University of Nebraska-Lincoln as an Assistant Professor. He moved from California Institute of Technology where he held a position of Postdoctoral Scholar. At his new affiliation, he is investigating structure-property relationship of electroactive active materials. Particularly, he is working on such EAPs as ionic polymer metal composites (IPMC) and ferroelectric polymers. Jiangyu can be reached at jli2@unl.edu or 402-472-1631.

Kenneth Meijer

In September, Kenneth Meijer started a joint faculty position at the Department of Biomedical Technology at the Technical University of Eindhoven, Netherlands www.bmt.tue.nl and the Department of Health Sciences at the University of Maastricht, Netherlands www.fdgw.unimaas.nl. During his post-doctoral research with Dr. Robert Full, at the Department of Integrative Biology at the UC Berkeley http//polypedal.berkeley.edu, he studied how biology can provide inspiration for the development of artificial muscles. He initiated the first direct comparison between biological muscles and several EAP actuators [*SPIE Proceedings 2000 and 2001; Electroactive Polymer (EAP) Actuators as Artificial Muscles, Ed. Y Bar-Cohen, Ch2.2, 2001*]. His studies showed that EAP actuators can operate within the performance space of biological muscles and have the potential to be used as artificial muscles. At his new affiliations his research will be directed at the study of locomotion in able and disabled people. He plans incorporate his work on artificial muscles within this research scope. Specifically, he intends to apply the EAP technology to develop smart rehabilitation devices, like lower limb prosthetics. It is his assertion that EAP actuators are perfectly suited to combine, in a simple and robust design, the actuation and sensing properties that are needed for an efficient prosthetic device that assists locomotion in a natural way. His new e-mail address is: kenneth.meijer@bw.unimaas.nl

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José-María Sansiñena

In May, José-María Sansiñena moved from NDEAA Tech. of the NASA's Jet Propulsion Laboratory (JPL), Pasadena, California to the Bioscience Division at the Los Alamos National Laboratory (LANL) in Los Alamos, New Mexico. This move will keep him in the area of EAP actuators based on Conducting Polymers (CP), for which he is studying macro and microactuators with a new monolithic configuration based on "Polyaniline Integrally Skinned Asymmetric Membranes" (PANI ISAMs). His experience in this field includes the construction of an electromechanical actuator based on a trilayer polypyrrole/solid-polymer-electrolyte/ polypyrrole (PPY/SPE/PPY) operating in air. This result was an important milestone for this field because it demonstrated the ability to produce actuators based on CPs that do not require a liquid environment. This work is helping pave the way for new applications for conducting polymers as electromechanical actuators. His new e-mail is josemari@lanl.gov and his phone number is 505-665-3501.

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

1st AIST Conf. on Artificial Muscles

On December 13-14, 2001, the "First AIST Conference on Artificial Muscles" was held at National Institute of Advanced Industrial Science and Technology (AIST), Osaka, Japan. This international conference was organized by the Special Division of Human Life Technology of AIST. The Chair was Takahisa Taguchi and the Secretary General was Kinji Asaka. This conference was well attended with about 130 attendees and the program included 14 invited papers and 9 posters covering various aspects of the field.

The invited lectures on the first day included papers about IPMC (K. Oguro, S. Tadokoro, and M. Shahinpoor), carbon nanotube (R. Baughman), conductive polymers (O. Inganäs, and T. Otero) and bio-muscles (T. Yanagida). Unfortunately, Y. Bar-Cohen, JPL, could not attend even though he was an invited speaker and a member of the organization committee. In place of his lecture a video about EAP, which he edited, was presented. On the second day the invited lectures that were presented included conductive polymers (W. Takashima, G. Wallace), non-ionic polymer gel (T. Hirai), theoretical formulation of the dynamics of polymer electrolyte gels (M. Doi), liquid crystalline elastomers (P. Auroy), man-machine interface in relation with artificial muscles (D. de Rossi) and artificial muscles smart gels with supramolecular structure (Y. Osada). In the concluding remark, de Rossi pointed out important aspects about the direction for the research of artificial muscles. He suggested it is necessary to establish: science of physically active materials, industry of artificial muscles, etc. The conference was well attended and stimulating discussions took place inspired by exceptional presentations. The proceedings is currently being prepared for and the abstracts can be obtained by sending an e-mail request to asaka-kinji@aist.go.jp

2001 MRS Fall Meeting

In this year MRS Fall Meeting a Symposium on EAP was included for the second time. This symposium was held in Boston from Nov. 26 to 27, 2001. The objective of this symposium was to provide a forum for the EAP researchers to exchange information, stimulate discussions and present the recent advances. The organizers were 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 were: 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). The proceedings for this Symposium is expected to be published soon and it would be available from MRS.

2002 ASME

Papers are being sought for a mini-symposium on polymeric actuation and sensing technologies as part of the ASME 2002 Adaptive Structures and Materials Symposium. The Adaptive Structures and Materials Symposium is part of the ASME International Mechanical Engineering Congress and Exposition being held in New Orleans, November 17-22, 2002. The purpose of the mini-symposium is to bring together researchers in the field of polymeric actuation and sensing. Papers are being requested in topics such as,

- materials fabrication techniques, analysis and modeling
- novel methods for sensing and actuation
- new and novel transduction technologies and modeling
- control methods for polymeric actuators and sensors
- applications of polymer sensors and actuators

To submit an abstract or if you have questions please contact Donald Leo, CIMSS / Mechanical Engineering Department, Virginia Tech, at donleo@vt.edu. A 300-word abstract is due March 1, 2002. General conference information can be found at www.asme.org, and the call for papers of this ASME meeting can be found at http://www.asme.org/congress/cfp/adaptive.htm.

2002 SPIE EAPAD Conference

Since the first SPIE conference on EAP that was held in March 1999, the field of EAP has emerged from its anonymity to the spotlight of the science and engineering community. Further, the SPIE's EAPAD conference has growth in numbers of participants and submitted papers. The conference is held over four days and the presentations are covering a broad range of topics from analytical modeling to application. The program of the EAPAD 2002 Conference is now available on: http://spie.org/conferences/programs/02/ss/confs/4695.html The papers are going to focus on issues that can help transiting EAP to practical use, including better understanding of the principles responsible for the electro-mechanical behavior, improved materials, analytical modeling, processing and characterization methods as well as considerations of various applications.

The upcoming conference will be opened with another interesting and exciting Keynote presentation. The speaker will be Cynthia Breazeal from MIT and the topic of her presentation is "Biologically inspired intelligent robots." In this presentation she is going to share her extensively experience with such robots that could benefit from EAP and an example is shown in Figure 1 where the robot Kismet is shown to react to her expressions including smiling. This topic of biomimetic robots is currently the subject of a book that is in preparation by Cynthia and the Editor of this Newsletter (see further information at the end of this issue).

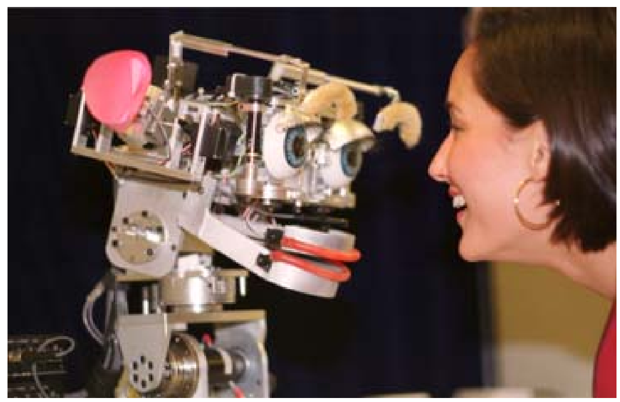

FIGURE 1: The Keynote Speaker, Cynthia Breazeal, MIT, with her Kismet robot responding to her expressions (courtesy of MIT Press Office) [http://www.ai.mit.edu/people/cynthia/cynthia.html].

As in the previous EAPAD conferences, we are going have another EAP-in-Action Session where some of the latest practical implementations of EAP will be demonstrated. This Session is a forum of interaction between the technology developers and potential users and it offers a "hands-on" experience with this emerging technology. During this session, the attendees are given opportunity to see demonstrations of EAP actuators and devices.

On Wed. March 20, an Open Panel Discussion Session will be held to debut the status of the field of EAP. The conference Chair, Cochair, and the invited speakers will serve as the discussion panelists. Each of the panelists will be given an opportunity to make a short statement and the attendees will be invited to express their thoughts and to debut the topics that will be presented. This session is intended to stimulate ideas and thought and help define the future direction of the development of EAP.

2002 Transducing Materials & Devices Conf.

From October 31 to November 1, 2002, the first Transducing Materials & Devices Conference is going to be held in Brügges, Belgium. Generally, transducing materials play an important role in our daily life enabling the functionality of many instruments and devices that are commonly used. Effective use of transducing materials requires understanding their behavior and assuring their robustness. These materials offer enormous potential to many fields and to name few one can list such important devices and mechanisms as single, multi-DoF and hybrid actuators, sensors, displays, MEMS, SAW, ultrasonic motors (USM), and reconfigurable robots. While there is a large body of science and engineering work that addressed the various transducing materials we are faced with many challenges. This conference is seeking to provide a forum for information exchange among the experts from the various related disciplines. The resulting interaction is hoped to lead to new initiatives and help existing technologies as well as forge new ones.

This Conference will be held as part of the Optatech 2002 Symposium, Photonic Systems Europe. The coordinator of this SPIE Symposium is M. Stiles, mikes@spie.org The conference Chair is Y. Bar-Cohen, yosi@jpl.nasa.gov and the Co-Chair is Kenji Uchino, Penn State University. The call for papers is expected soon and the due date for abstracts is April 1, 2002.

EAP ADVANCEMENTS

ABB Corporate Research Ltd, Switzerland

Actuation needs for fluid flow guiding vanes

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Fluid guiding vanes for reversible machinery should enable the switching of the fluid flow from one favored direction to another within a few seconds. The guiding vane application requires large displacements (90° twist minimum) in a few seconds and the use of low voltage. Traditionally, the solution involves a blade with a fixed geometry being able to rotate using a small engine. Smart materials were thought as great candidates to simplify the current set-up and eliminate the need for the engine.

Ionic polymer matrix composites were ordered from Biomimetics Products, Cedar Crest (NM, USA). The material showed a 180° reversible twist under 5 Volts in 2 seconds (See Figure 2). However, the electro-active polymer could not be directly used as a guiding vane for two following reasons: first the lack of stiffness to properly guide the flow and the constant need for current to maintain the bent shape, that would not lead to a cost-viable solution.

It was then thought to use an unsymmetrical composite laminate exhibiting two tailorable stable positions. The feasibility of this concept was proven using a bi-stable carbon fiber AS4/thermoplastic PEEK composite plate actuated using shape memory alloys (SMA) as shown in Figure 3 (invention disclosure filed). This system enabled the blade twist in less than 2 seconds. However, embedding shape memory alloys in polymers is a difficult task, often limited by a phase transition temperature of the SMA lower than the composite processing temperature. Furthermore the use of a "glue" to fix the SMA on the blade surface disturbs the surface state of the blade (important for fluid flow) and also leads to very short lifetime characterized by the delamination of the SMA under cyclic loading.

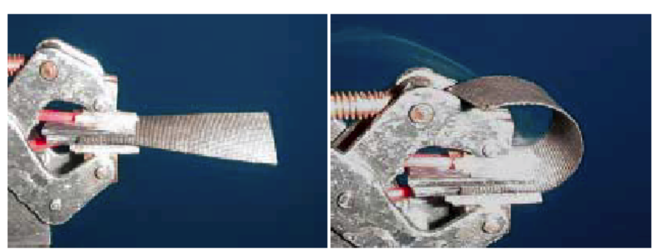

FIGURE 2: Biomimetic ionic polymer matrix composite response to 5Volts.

The last step would therefore be to combine the use of electro-active polymers and bi-stable composite blades to achieve a compact, cost-effective guiding vane. The electro-active polymer could be mechanically or chemically bonded to the 2

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outer surfaces of the blade and serve as the actuation mechanism. However, two technical shortcomings still hinder the realization of this next step:

FIGURE 3: Bi-stable composite guiding vane actuated by SMA.

1. The force developed by the electroactive polymer was not documented by the supplier and no data could be found in the literature. Performing a very simple experiment involving a common precision scale, enabled the determination of the force developed by the actuated polymer under 5V as a function of the sample length [Reference 1]. The results are shown in Figure 4. The maximum force obtained is rather small (0.06 N) and does not enable the actuation of a 100 x 100 x 1.5 mm AS4/PEEK composite vane.
2. 2. The second technical shortcoming is the need for humid environment. To function properly, the electroactive polymer requires constant wetting of the polymer. A solution should therefore be found enabling the use of the dry polymer or, more likely considering the physics of the actuation system, to find a solution to trap moisture within the polymer.

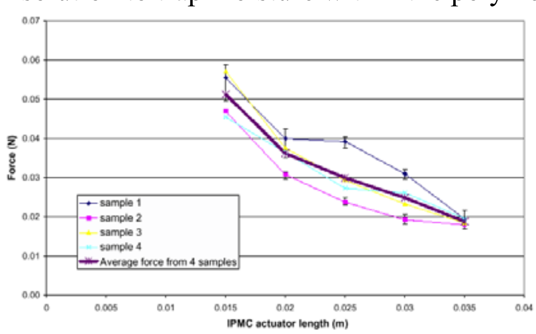

FIGURE 4: Force as a function of the actuation voltage for IPMC.

With the current technology, most traditional industrial products such as fluid flow guiding vanes are already optimized. However, solving these two technical challenges would open the door to the development of new cost-effective solutions.

Reference

Bunce, C., "Smart actuation of bi-stable composite laminates," Master Thesis, Imperial College, UK, Sept. 2000.

CAESAR (Aenter of Advanced European Studies And Research), Germany

Bistable micro-actuators by combination of polymers with shape memory thin films

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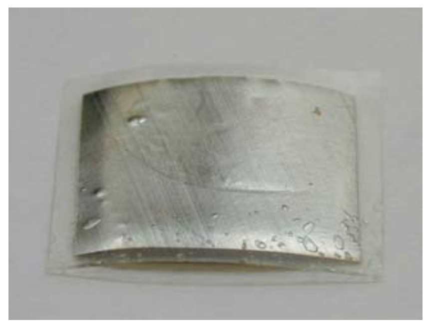
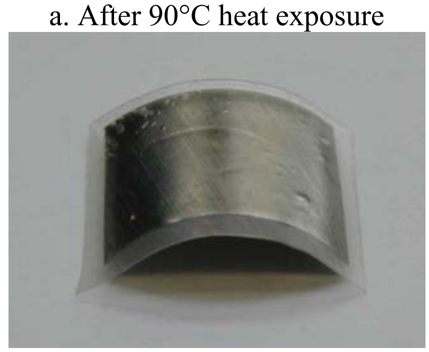


a. After 90°C heat exposure



b. After 120°C heat exposure

FIGURE 5: Photos of the bistable actuator taken at room temperature.

Shape memory composites (SMC) provide high work output when the shape memory alloy undergoes the martensitic transformation. However to reach and hold the bended position of the SMC it is necessary to apply continuous thermal energy. This drawback can be avoided by combining the SMC with a suitable polymer. The polymer fixes the flat and the bended shape (see Figure 5) of the SMC if the glass transition temperature is within the hysteresis of the shape memory alloy (see Figure 6).

Therefore, energy is only necessary for switching the actuator from one shape to the other.

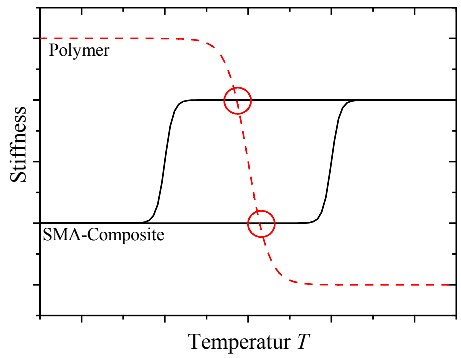


FIGURE 6: Principle of the bistable shape-memory-polymer actuator

The benefit of this actuator is the simple setup where the functionality is independent of constructional boundary conditions and as such it can be built very small with high mechanical work output and large deflection. Applications include e.g. relays, adjustable capacitors, and micro-grippers.

The Danish Polymer Centre, Denmark

Dielectric elastomer actuators (DEA)

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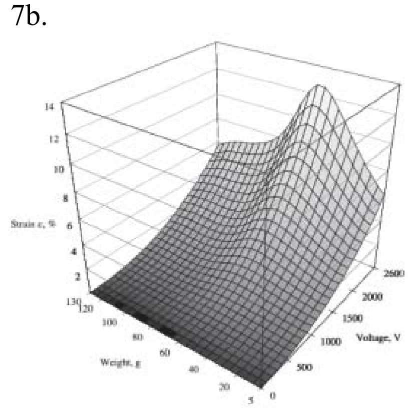
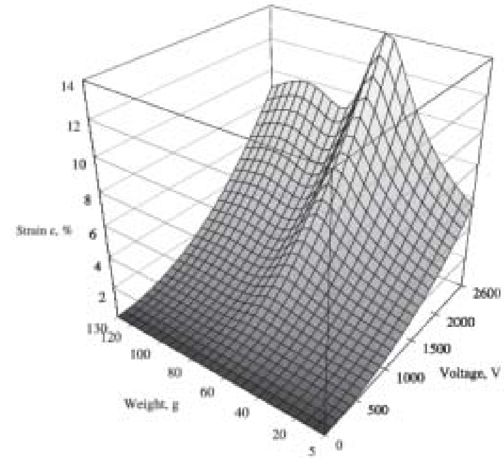
Recent characterizations of dielectric elastomer actuators (DEA) and models for their behavior can be found in the Ph.D. thesis from Guggi Kofod: http://www.risoe.dk/rispubl/POL/ris-r-1286.htm An example of results that are included in this thesis is given in Figure 7 where the expansion of a DEA actuator made from poly-dimethylsiloxane is presented. In Figure 7a the data is shown and the fit to the model in shown in Figure 7b.



a. Engineering strain data.



b. Engineering strain calculated from the model. The dielectric constant was set to ε=2/3

FIGURE 7: Extension of actuator as a function of load and applied voltage.

Jet Propulsion Laboratory (JPL)

EAP surface wiper for biofouling and bubbles removal from Electrochemical sensors

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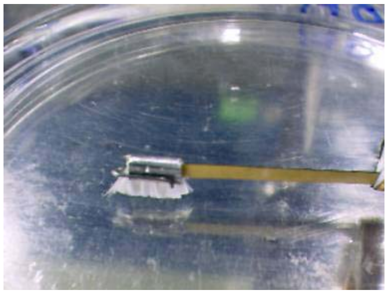
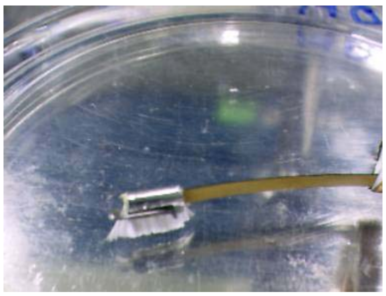
Recently, a pilot study has been initiated under the NASA NRA-00-HEDS-01 program, having potential use of EAP in space application. This study is part of the task entitled "Surface Control of Electrochemical Sensors for Water Reclamation." The goal of this project is to develop a wiper that is possibly actuated by EAP to ameliorate problems of biofouling and bubbles that obscure sensor surfaces in microgravity. An IPMC strip with a miniature brush was made to support the preliminary experiments and the proof of concept (Figure 8). In support of this objective, AIST, Japan, is currently preparing IPMC strips under the lead of Dr. Kinji Asaka. It is hoped that success of this study will be followed by an experiment on the Space Shuttle. A breadboard EAP wiper was made (active IPMC strip: L=3cm, W= 3mm, and t=0.2mm) as shown in Figure 8 both in steady and activated states. The key concern is the low actuation force that is produced by IPMC. Alternative electroactive materials from the EAP community to this task will be welcomed and properly acknowledged.



V = 0 V



V = -1 V

FIGURE 8: IPMC: Nafion/Li+ 0.2 mm thick, Voltage: ±1.5V, Tip displacement: ±12 mm.

Acknowledgement
Initially, the Principal Investigator (PI) for the "Electrochemical Sensors for Water Reclamation" task has been Michael Hecht and the current PI is Martin Buehler.

EAP characterization – IPMC time dependent response

Y. Bar-Cohen, yosi@jpl.nasa.gov, X. Bao, JPL

Most past studied of Ionic Polymer-Metal Composite (IPMC) were focused on the effect of the ions on the material electroactivity [Bar-Cohen, 2001; Nemat-Nasser and Thomas, 2001]. Our recent studies comparing the behavior of Nafion/Li+ and Flamion/TBA+ revealed that the time response of these materials is significantly different. Nafion/Li+ reacts quickly in one direction and then relaxes back (Figure 9); on the other hand, Flamion/TBA+ bends slowly over several hundreds of minutes (Figure 10). A macro theoretical model was developed to express the back relaxation and the test results showed a good fit to the experimental data (Figure 9).

This result that IPMC behavior is highly dependent on the backbone/cation was observed during the ongoing efforts to develop methods for the characterization of EAP materials [Stewart and Bar-Cohen, 2001]. An experimental setup was developed for data acquisition from IPMC strips subjected to various signal amplitude and voltage levels as well as tip mass loads. Using a video setup and an image-processing algorithm the EAP strip deformation is tracked. It was determined that a system with 30Hz frame/sec is too slow to acquire the initial deformation of the Nafion/Li+ IPMC. A new system was recently established that allows acquisition at rates of up to 125 frames/sec (Figure 11).

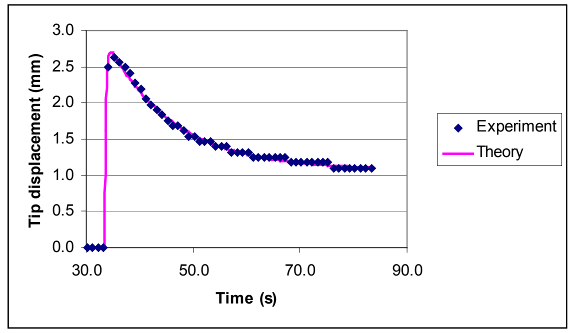


FIGURE 9: Time response of Nafion/Li+ IPMC strip and comparing with new theoretical model.

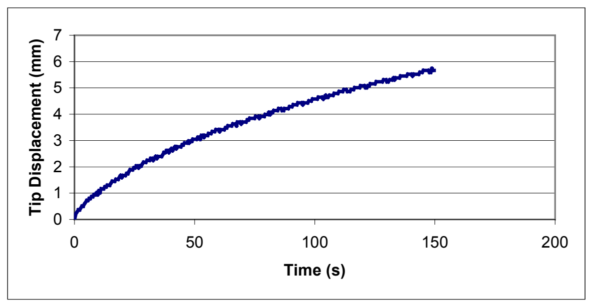


FIGURE 10: Time response of Flamion/TBA+**.**

FIGURE 11: Setup for data acquisition of the curvature as a function of various parameters for IPMC.

The new measurement setup allows capturing 2D images of IPMC large deformations (Figure 12). From the real time captured data the strip curvature is extracted as a function of the input voltages, currents and tip force, where the signal shape is controllable.

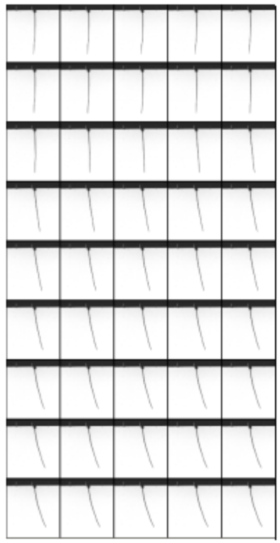


FIGURE 12: Sequence of displacements captured at 125 frames/sec for Nafion/Li+ IPMC.

Acknowledgement

This study was conducted under the DARPA's EAPAD contract. The Nafion base IPMC was provided by M. Shahinpoor from ERI and the Flamion base IPMC was provided by K. Oguro, AIST.

Reference

Bar-Cohen Y. (Ed.), "Electroactive Polymer (EAP) Actuators as Artificial Muscles - Reality, Potential and Challenges," SPIE Press, ISBN 0-8194-4054-X, (2001).

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.

Space and commercial applications of Cold Hibernated Elastic Memory (CHEM) self-deployable structures

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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. The CHEM processing cycle is illustrated in Figure 13 below.

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. One of examples is the demonstration of CHEM wheels developed for the sub-scale nano-rover. Other potential applications, such as a horn antenna, camera mast, and a sensor delivery system, were studied under various programs at JPL. Besides space structural use, the impact energy absorption applications such as self-deployable soft landing systems and micrometeoroid protection shielding were considered and investigated lately with promising preliminary results.

Although space community is the major beneficiary, a lot of potential commercial applications are foreseen for the "earth environment". The researchers have been already contacted regarding potential CHEM applications in recreation, toy, automotive and biomedical areas.

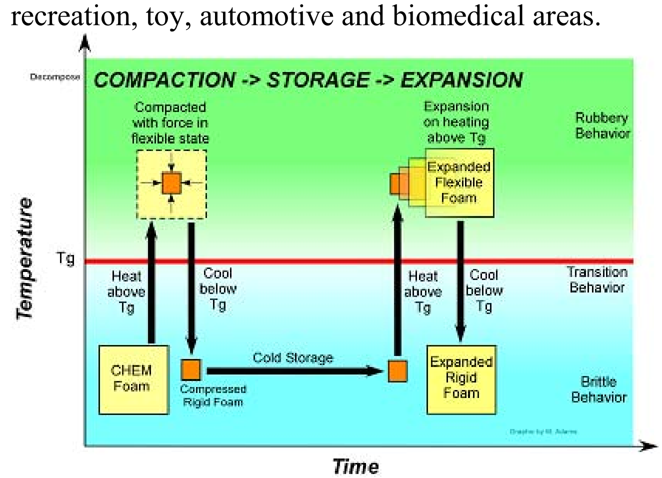

FIGURE 13: CHEM processing cycle.

Leeds University, UK

Force and position control for artificial muscles

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New actuator technologies are moving closer towards the creation of artificial muscles. For these muscles to behave in synergy with natural human muscle they must be controlled in a similar manner. It has been postulated that the control of human motion is achieved through a force and position control strategy termed *impedance control* [1]. Impedance control does not control either force or position but rather compromises between the two conflicting demands. This relationship between force and position is specified as a mass, spring and damper system.

An impedance controller has been created from a PID position controller and impedance filter feedback loop (Figure 14) [2]. In a position only controller, the control aim is to track a desired position as closely as possible. In this situation the controller still tracks the desired position as closely as possible, however external forces now influence it. The result of the impedance controller applied to a strip of IPMC is shown in Figure 15.

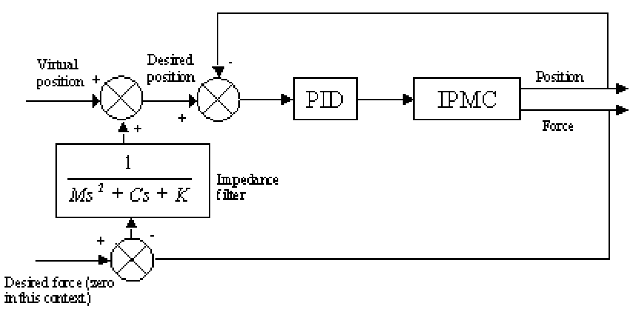

FIGURE 14: Impedance controller block diagram.

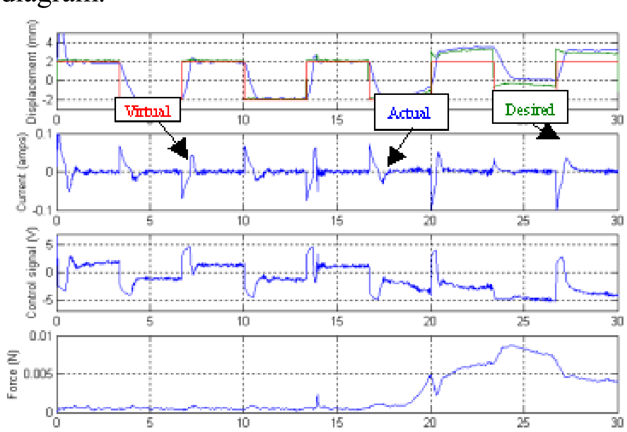

FIGURE 15: Controller response

The desired position and virtual position are identical for the first 15s as no external force is present. After 15s external forces alter the desired position with the actual position accurately tracking this change.

The external force has modified the IPMC behavior in a predicable manner with the impedance characteristics determining whether the actuator or environment is dominant. It is vital that artificial muscles are controlled by force and position control if they are to successfully interact with their environment.

Acknowledgements
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Reference

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Los Alamos National Laboratory (LANL)

Chemical and Electrochemical Polyaniline Actuators with a Novel Monolithic Configuration: Integrally Skinned Asymmetric Membranes (PANI ISAMS)

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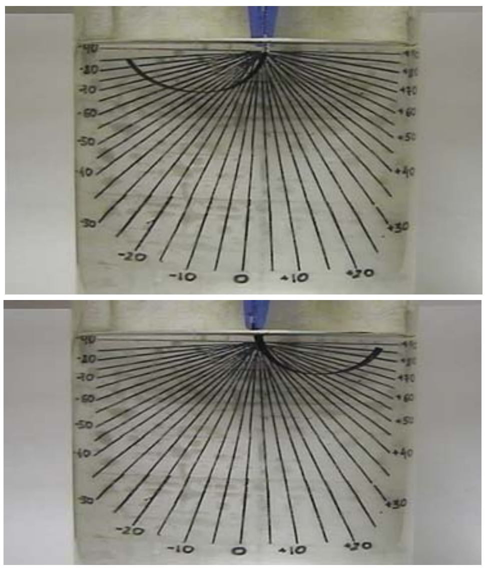
Despite recent successes in the development of conducting polymer actuators, bimorph type actuators are still suffering from the fact that they delaminate after long working cycles. This failure is caused by the fact that the physical adhesion between layers cannot sustain repeated volume alteration at the interface. Further, the efficiency of the actuator is lower because bimorph structure increases the weight of the device and part of the input energy is consumed from stress generated at the interface.

The aim of this study is to overcome these limitations of bimorph actuators through the construction of new chemical and electrochemical actuators with a novel monolithic structure based on a single "polyaniline integrally skinned asymmetric membranes (PANI ISAMs)". These membranes consist of a thin dense skin layer of submicron thickness and a porous substructure where the density varies from the skin side (dense) to the porous side. This porous (density) gradient is crucial in determining the performance of chemical and electrochemical actuators.

Chemical actuators are achieved by immersing PANI ISAM into an acidic solution that causes chemical doping of the polyaniline chains. This fact promotes density-dependent volume expansion, varying within the membrane that leads to a bending movement toward the porous side (Figure 16A). On the other hand, the immersion into a base solution (1M NH_4OH) promotes a dedoping process leading to a bending movement toward the skin side (Figure 16B).

A)



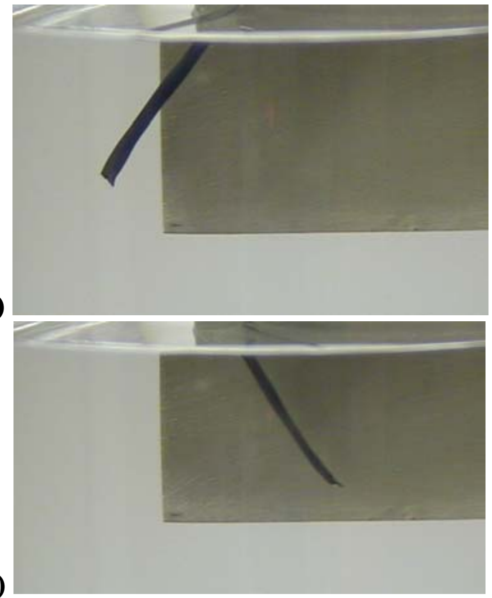
B)

FIGURE 16: Bending movement of a PANI ISAMs chemical actuator through chemical doping. A) 0.1M HCl aqueous solution; B) 4.0M NH4OH aqueous solution.

In parallel with the study of chemical actuators described above, we have been developing electrochemical actuators based on a single free standing PANI ISAM. When an anodic potential is applied the density-dependent volume change created along the cross-section of the PANI membrane generates an expanding stress gradient that promotes a bending movement of the free end toward the less dense side (Figure 17A). The following reduction process causes a contracting stress gradient that is relaxed during the bending of the actuator toward the denser side of the PANI membrane (Figure 17B). To the best of our knowledge, this is the first time that both chemical and electrochemical monolithic CP actuators were constructed based on the same material.

Acknowledgements
We thank financial support from the Laboratory Directed Research and Development (LDRD) fund from Los Alamos National Laboratory (DOE), and the Cross Enterprise Technology Development Program from National Aeronautics and Space Administration, NASA.

A)



B)

FIGURE 17: Movement of an electrochemical actuator constructed with a free standing PANI membrane under a square wave of potential with a frequency of 0.5 Hz (from –1V (1 s) to 1.5V (1 s) vs. SCE) in a 1.0 M HCl aqueous solution. A) application of an anodic potential (1.5 V vs. SCE); B) application of a cathodic potential (- 1 V vs. SCE).

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New Partial Fluoro-Ionomer for Electroactive Polymer Composite

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Materials Research Laboratories of Industrial Technology Research Institute in Taiwan has recently found a new type of electroactive polymer composite (EAPC with Pt electrode) made from polyvinylidene fluoride (PVDF) based partially onfluoro-ionomer (PFI) with fluoro- or carbon/hydrogen-polymer matrix.

Film Properties	
Conductivity (S/cm)	10^{-2}~10^{-3}
Tensile strength (Kg/cm^2)	230~310
Swelling ratio (%)	10~45
Decompose temp. (°C)	>250

	MRL Nafion™/Pt	MRL F-Ionomer/Pt
Driving voltage (Volt, 0.5Hz)	< 5	< 5
Displacement (mm)[a]	0 ~ 20	0 ~ 24
Bending life (hr)[b]	1.6	14.5
Bending life (hr)[b-1]	0.13	0.79
Tip force (g)[c]	0.120	0.122
Work density (KJ/m^3)	0.10	0.11

a: specimen size(3mm×30mm×0.2mm) ; at 5V, 0.1 ~ 0.5Hz
b: in 0.1M Na_2SO_4+10mM H_2SO_4 solution; at 5V, 0.5Hz
b-1: in air; at 5V, 0.5Hz
c: specimen size(4mm×35mm×0.2mm) ; at 5V, 0.5Hz

These EAPC/Pt bend in response to low-voltage electric stimuli (<5 Volts), the generated force is about the same scale as the Nafion/Pt, but with 6~9 times bending lifetime. Properties of these EAPC including stiffness, stress, strain, tensile strength and bending curvature can all be tailored easily by simply changing its composition ratio. The fabrication of PFI composite actuators can be simple and low cost.

NASA-Langley Research Center & CIMSS

Measurement of Output Force of Bending Actuators Using Electrostrictive G-Elastomers

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Recently, a new class of electrostrictive polymers-electrostrictive graft elastomers (g-elastomers) was developed at NASA Langley Research Center. In this work, the tip output force of bending actuators using the materials was measured to understand dependence of performance of the actuators on configuration. Therefore, better actuator can be designed and fabricated. The output force of the actuators strongly depends on their length and the applied electric field. For the actuator tested that is 40 micrometer thick, the tip output force increases from 133 micro-Newton at 33.5-mm position from the fixed end of the actuator to 638 micro-Newton at 7 mm position. According to the curve fitting by a power relationship between the tip output force and the test position, for a 1 mm bending actuator with the same thickness (40 micrometer), the tip output force can be about 1 mN. The experimental set-up for the force measurement and the test results are shown in Figure 18 and Figure 19, respectively.

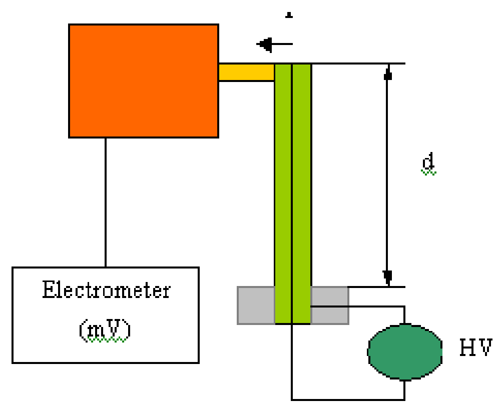

FIGURE 18: Schematic of output force measurement of bending actuators using electroactive polymers.

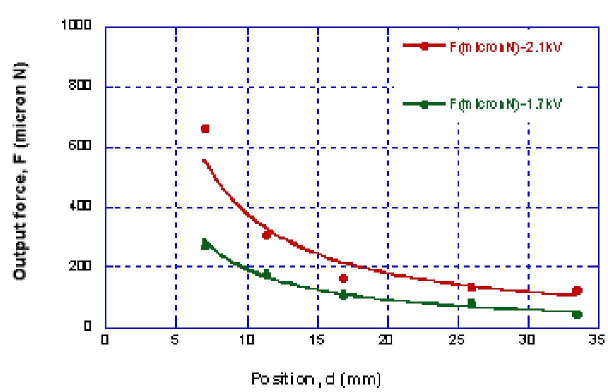

FIGURE 19: Output force of bending actuators using electrostrictive graft elastomers.

SKK and UNR cooperation

Electrostrictive polymers based upon novel nano-composite processes

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A research team from SKK University of Korea and University of Nevada-Reno is developing a number of new electrostrictive polymers based upon novel nano-composite processes. Realizing that a key engineering to the success of modern advanced materials is their tailored material behavior, an effective way to obtain desirable macroscopic properties is related to nano-level materials processing. A new nano-composite, made with intercaliated/exfoliated organo-modified montmo-rillonite-"Cloisite", via polyurethane synthesis, is of interest. A successfully synthesized polyurethane nanocomposite showed a drastic increase in both the dielectric constant and ionic conductivity. Such an improvement can be directly translated into a large reduction of operating voltages that is a definite benefit for electrostrictive polymer artificial muscles.

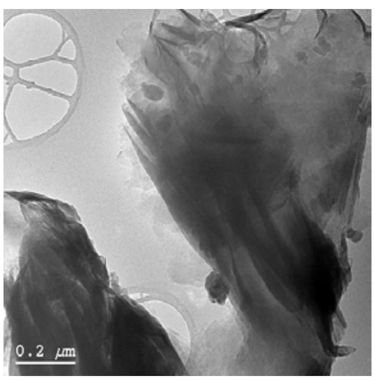

FIGURE 20: A TEM of nano-structured plates – montmorillonite.

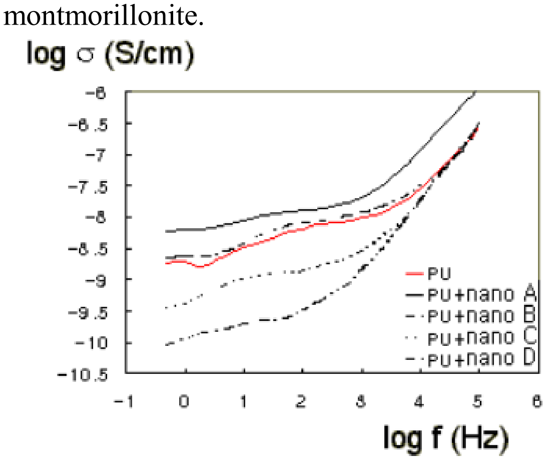

FIGURE 21: Electric conductive vs. frequency.

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Towards Artificial Muscles

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The performance of legged robots could be greatly improved if they have muscle like actuators at their disposal. Biological muscle is a magnificent actuator with the capacity to perform many functions. Muscles have good energy density values and they integrate actuation, support and fuel systems. Compared to human-made actuators, muscles are considered to be compliant actuators, which may be one of the reasons why animals are capable of agile locomotion in unstructured environments where legged robots fail. Muscles in the animal kingdom vary greatly with respect to their performance[1]. Maximum stress varies by 100-fold (0.7 to 80 Ncm^{-2}) as does the velocity at which muscles contract (0.3 to 17 lengths/sec). Frequencies of operation range from less than 1 Hz to 1000 Hz. Mass-specific power output can reach over 250 W/kg muscle.

To study if EAP can be considered as artificial muscles we have measured the functional workspace of EAP actuators using the same setup and techniques that we use to test biological muscle [2, 3]. Thus far we have evaluated the properties of three different EAP materials; the acrylic (*VHB 4910 acrylic*) and silicone (*CF19-2186*) dielectric elastomers developed at 'SRI International' and the high-energy electron-irradiated co-polymers (*P(VDF-TrFE)*) developed at the MRL laboratory at Penn State University.

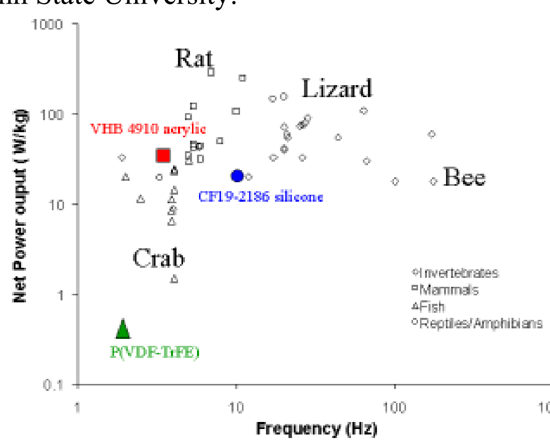

FIGURE 22: Mass-specific power output of biological muscles (open symbols) and three different EAP actuators (colored symbols) as a function of the frequency of oscillation. Data were obtained using the workloop method.

Results for mass specific power output (Fig. 1) indicate that the EAP materials partly capture the functional workspace of natural muscle. Based on our analysis we conclude that EAP technologies have great potential to be applied as artificial muscles.

Currently, we are investigating the functional workspace of *IPMC* actuators developed at the Artificial Muscle Institute at the University of New Mexico and *Liquid Crystalline Elastomers* of the Naval Research Laboratory.

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3. Meijer, K, Rosenthal, M and Full, RJ, 2001, SPIE.

BOOKS & PUBLICATIONS

Biologically-Inspired Intelligent Robots

Y. Bar-Cohen and C. Breazeal (Editors)

With today's technology one can quite well graphically animate the appearance and behavior of biological creatures (e.g., Shrek and other cartoon movies). Advances in biomimetics are increasingly making it feasible to emulate creatures to the point that viewers will eventually react with "gosh, this robot looks so real!" just like the reaction to an artificial flower. There is already extensive heritage of making robots and toys that look and operate similar to human, animals and insects. The emergence of artificial muscles is expected to make such a possibility a closer engineering reality. A book, entitled "Biologically-Inspired Intelligent Robots," covering this topic of biomimetic robots is currently in preparation and it is expected to be published towards the end of 2002. The cover page of the book (Figure 23) presents the challenges to making such robots in terms of appearance, operation, facial expression, stability, robustness, etc.

The issues that are involved are multidisciplinary and they including: materials, actuators, sensors, structures, functionality, control, intelligence and autonomy. It is interesting to address these technical issues but there are also fundamental ones that also need to be addressed. Some of these issues include self-defense, controlled-termination and many others. Inspiration from science fiction sets expectations that will continually be bound by reality and the state of the art. Effectively, this book is about the electro-mechanical equivalence of cloning and …., who knows, as these robots become more engineering reality they may rise to become a topic of public debut similar to the topic of cloning biology.

The draft of the book outline is accessible on: http://ndeaa.jpl.nasa.gov/ndeaa-pub/Biomimetics/Biomimetic-robots-outline.pdf

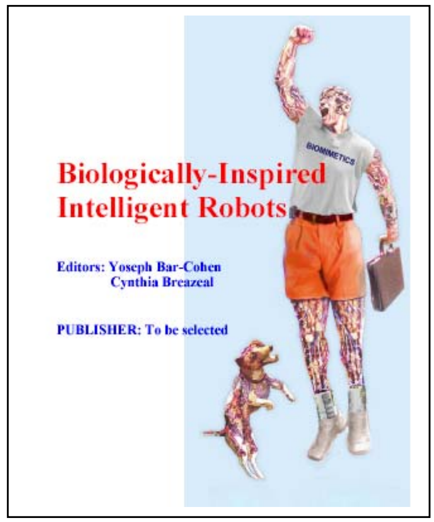

FIGURE 23: The cover page of the upcoming book on biomimetic robots. This book will describe the state of the art and challenges to making such robots (The shown graphics is a courtesy of David Hanson, Entrepreneur).

UPCOMING EVENTS

March 18-22, 2002	EAPAD 2002, SPIE joint Smart Materials and Structures and NDE, San Diego, CA., P. Wight patw@spie.org Website: http://spie.org/conferences/programs/02/ss/confs/4695.html
March 18-21, 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 23-28, 2002	14th U.S. National Congress "Soft Actuators and Sensors," Virginia Tech, S. Nemat-Nasser, www.esm.vt.edu/usncam14/
Oct. 31 – Nov. 1, 2002	Transducing Materials & Devices, part of Optatech 2002, Photonic Systems Europe, Belgium, SPIE, Y. Bar-Cohen, yosi@jpl.nasa.gov
Nov. 17-22, 2002	Adaptive Structures and Materials Symposium, ASME 2002, New Orleans, D. Leo, donleo@vt.edu
Dec. 9-11, 2002	Biomimetics and Artificial Muscles, Albuquerque, NM, M. Shahinpoor shah@unm.edu

WorldWide Electroactive Polymers (EAP) Newsletter

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