

# **ELECTROACTIVE POLYMERS AS ARTIFICIAL MUSCLES**

## **REALITY, POTENTIAL AND CHALLENGES**



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**SPIE EAPAD - Short Course**

**March 6, 2005, San Diego, California**

# Outline

- Background and history
- Electroactive polymers as artificial muscles
- The EAP infrastructure
- EAP application considerations
- Concluding remarks

# What is an Electroactive Polymer (EAP)

- Certain polymers respond to stimulation with a change that can be temporary or permanent. The source for stimulation may include heat, light, chemicals, pressure, magnetic and electric field as well as others.
- EAP materials are polymers that respond to electrical stimulation (field, current, etc.) with a change in property or characteristic
- Changes can involve physical deformation, optical or magnetic property variation and others.
- The emphasis of this course is on EAP materials that react to electrical excitation with mechanical change.

# Background

- Most conventional mechanisms are driven by actuators requiring gears, bearings, and other complex components.
- Emulating biological muscles can enable various novel manipulation capabilities that are impossible today.
- Electroactive polymers (EAP) are emerging with capability that can mimic muscles to actuate biologically inspired mechanisms.
- EAP are resilient, fracture tolerant, noiseless actuators that can be made miniature, low mass, inexpensive and consume low power.
- EAP can potentially be used to construct 3-D systems, such as robotics, which can only be imagined as science fiction using current capabilities.

# Historical prospective

- Roentgen [1880] is credited for the first experiment with EAP electro-activating rubber-band to move a cantilever with mass attached to the free-end
- Sacerdote [1899] formulated the strain response of polymers to electric field activation
- Eguchi [1925] discovery of electrets\* marks the first developed EAP
  - Obtained when carnauba wax, rosin and beeswax are solidified by cooling while subjected to DC bias field.
- Another important milestone is Kawai [1969] observation of a substantial piezoelectric activity in PVF2.
  - PVF2 films were applied as sensors, miniature actuators and speakers.
- Since the early 70's the list of new EAP materials has grown considerably, but the most progress was made after 1990.

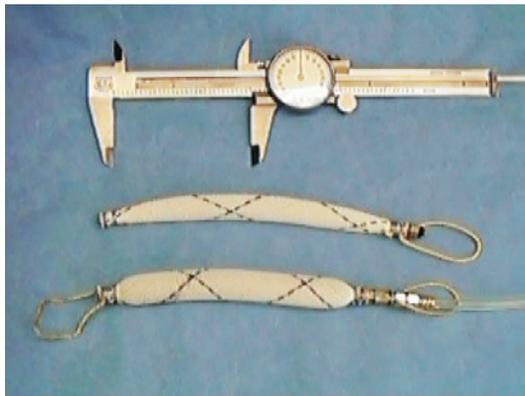
\* Electrets are dielectric materials that can store charges for long times and produce field variation in reaction to pressure.

# Non-Electro Active Polymers (NEAP)

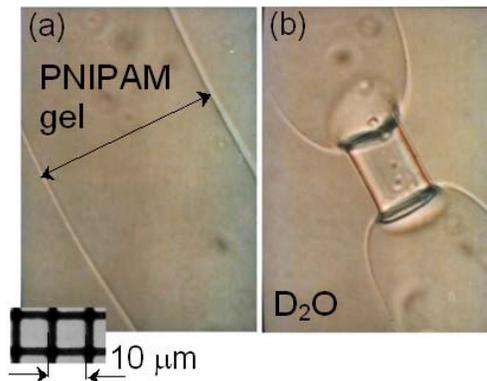
- Conductive and Photonic Polymers
- Smart Structures and Materials
- Deformable Polymers
  - Chemically Activated
  - Shape Memory Polymers
  - Inflatable Structures
  - Light Activated Polymers
  - Magnetically Activated Polymers

# Non-Electro Active Polymers (NEAP)

## Examples



**McKibben Artificial Muscles**  
Air Pressure activation  
(B. Hannaford, Washington)



**Laser Illuminated Polymer**  
Light activation  
(H. Misawa, U. of Tokushima, Japan)



**Shape Memory Polymers**  
Heat/pressure activation  
(W. Sokolowski, JPL)

## COMPARISON BETWEEN EAP AND WIDELY USED TRANSDUCING ACTUATORS

Property	EAP	SMA	EAC
Actuation strain	Over 300%	<8% (short fatigue life)	Typically 0.1–0.3 %
Force (MPa)	0.1–25	200	30–40
Reaction speed	μsec to min	msec to min	μsec to sec
Density	1–2.5 g/cc	5–6 g/cc	6–8 g/cc
Drive voltage	Ionic EAP: 1–7 V Electronic EAP: 10–150 V/μm	5-Volt	50–800 V
Consumed power *	m-Watts	Watts	Watts
Fracture behavior	Resilient, elastic	Resilient, elastic	Fragile

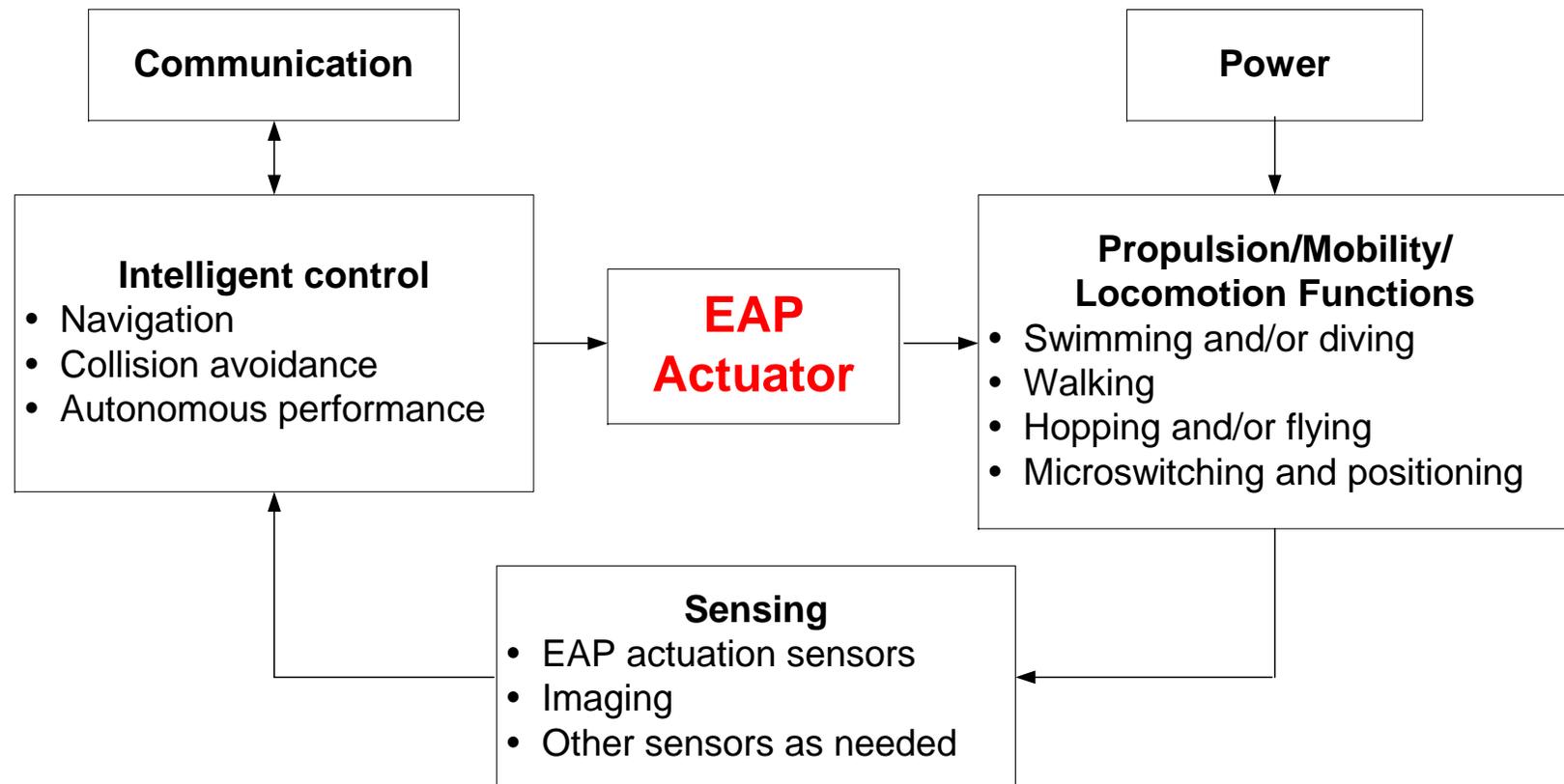
\* Note: The power consumption was estimated for macro-devices that are driven by such actuators.

## COMPARISON BETWEEN EAP AND WIDELY USED TRANSDUCING ACTUATORS

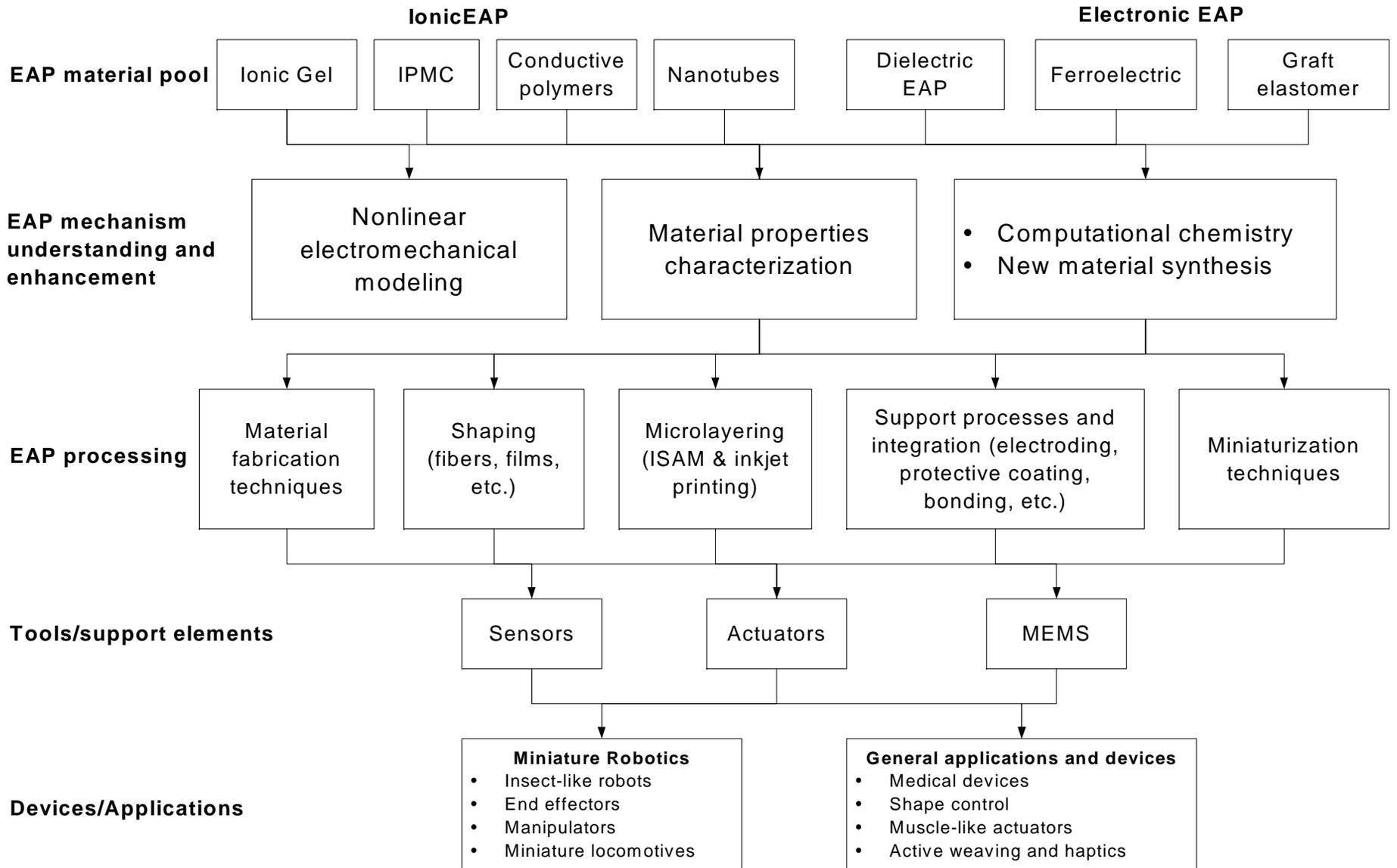
Property	Electrostatic silicone elastomer [Pelrine et al., 1998]	Polymer Electrostrictor [Zhang et al, 1998]	Single Crystal Electrostrictor [Park and Shrout, 1997]	Single Crystal Magnetostrictor [Hathaway and Clark, 1993]
Actuation strain	100%	4%	1.7%	2%
Blocking force/area *	0.2 MPa	0.8 MPa	65 MPa	100 MPa
Reaction speed	msec	$\mu$ sec	$\mu$ sec	$\mu$ sec
Density	1.5 g/cc	3 g/cc	7.5 g/cc	9.2 g/cc
Drive field	144 V/ $\mu$ m	150 V/ $\mu$ m	12 V/ $\mu$ m	2500 Oe
Fracture toughness	Large	Large	Low	Large

\* Note: This is the force that is required to block the actuator and it is normalized by its surface area. Values were calculated assuming the elastic properties were independent of applied field and are therefore approximated.

# ELEMENTS OF EAP ACTUATED DEVICES



# EAP infrastructure



# Electroactive Polymers (EAP)

## **ELECTRONIC EAP**

- Dielectric EAP
- Electrostrictive Graft Elastomers
- Electrostrictive Paper
- Electro-Viscoelastic Elastomers
- Ferroelectric Polymers
- Liquid Crystal Elastomers (LCE)

## **IONIC EAP**

- Carbon Nanotubes (CNT)
- Conductive Polymers (CP)
- ElectroRheological Fluids (ERF)
- Ionic Polymer Gels (IPG)
- Ionic Polymer Metallic Composite (IPMC)

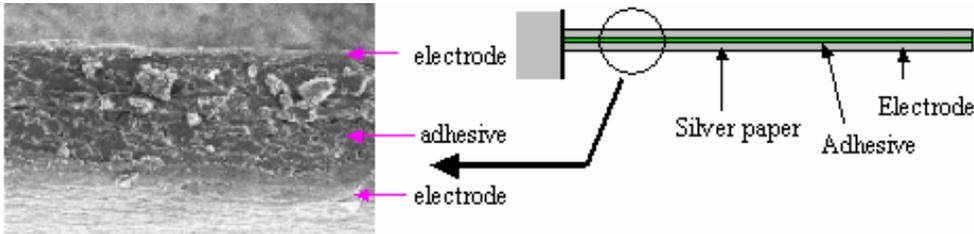
# Current EAP

## Advantages and disadvantages

EAP type	Advantages	Disadvantages
Electronic EAP	<ul style="list-style-type: none"> <li>• Can operate in room conditions for a long time</li> <li>• Rapid response (msec levels)</li> <li>• Can hold strain under dc activation</li> <li>• Induces relatively large actuation forces</li> </ul>	<ul style="list-style-type: none"> <li>• Requires high voltages (~150 MV/m). Recent development allowed for (~20 MV/m)</li> <li>• Requires compromise between strain and stress</li> <li>• Glass transition temperature is inadequate for low-temperature actuation tasks and, in the case of Ferroelectric EAP, high temperature applications are limited by the Curie temperature</li> <li>• Mostly, producing a monopolar actuation independent of the voltage polarity due to associated electrostriction effect.</li> </ul>
Ionic EAP	<ul style="list-style-type: none"> <li>• Produces large bending displacements</li> <li>• Requires low voltage</li> <li>• Natural bi-directional actuation that depends on the voltage polarity.</li> </ul>	<ul style="list-style-type: none"> <li>• Except for CPs and NTs, ionic EAPs do not hold strain under dc voltage</li> <li>• Slow response (fraction of a second)</li> <li>• Bending EAPs induce a relatively low actuation force</li> <li>• Except for CPs, it is difficult to produce a consistent material (particularly IPMC)</li> <li>• In aqueous systems the material sustains electrolysis at &gt;1.23 V requiring</li> <li>• To operate in air requires attention to the electrolyte.</li> <li>• Low electromechanical coupling efficiency.</li> </ul>

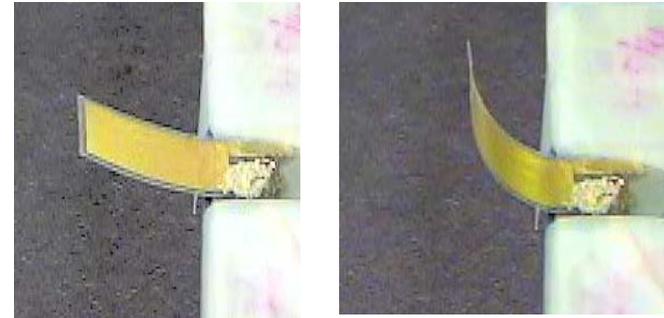
# Electronic EAP

## ELECTRIC FIELD OR COULOMB FORCES DRIVEN ACTUATORS



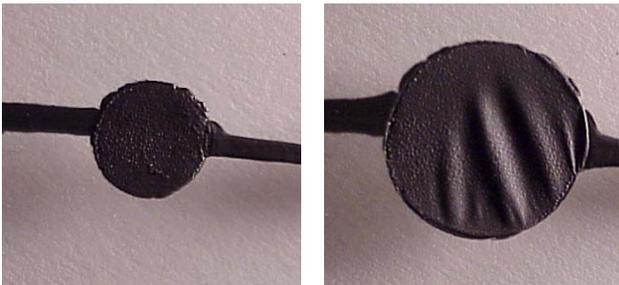
**Paper EAP**

[J. Kim, Inha University, Korea]



**Ferroelectric**

[Q. Zhang, Penn State U.]

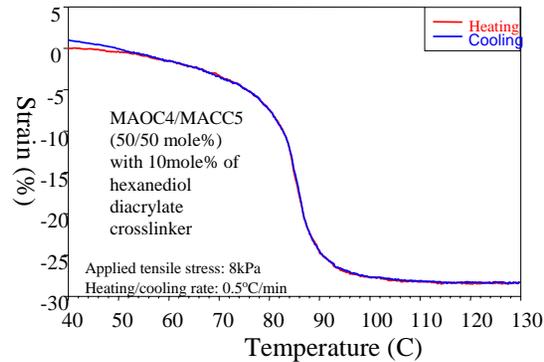


**Voltage Off**

**Voltage On**

**Dielectric EAP**

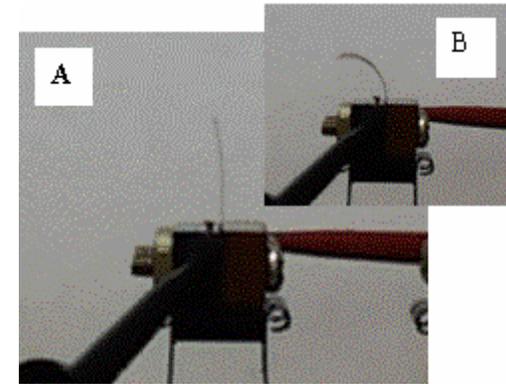
[R. Kornbluh, et al., SRI International]



**Liquid crystals**

(Piezoelectric and thermo-mechanic)

[B. R. Ratna, NRL]



**Graft Elastomer**

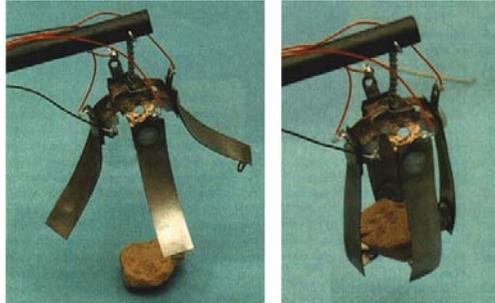
[J. Su, NASA LaRC]

# Electronic EAP

Actuator type	Principle	Advantages	Disadvantages	Reported Types
Ferroelectric Polymers	Polymers that exhibit noncentrosymmetric sustained shape change in response to electric field. Some of these polymers have spontaneous electric polarization making them ferroelectric. Recent introduction of electron radiation in P(VDF-TrFE) copolymer with defects in their crystalline structure dramatically increased the induced strain.	<ul style="list-style-type: none"> <li>• Induce relatively large strain (~5%).</li> <li>• Offer high mechanical energy density resulting from the relatively high elastic modulus</li> <li>• Permit ac switching with little generated heat</li> <li>• Rapid response (msec levels)</li> </ul>	<ul style="list-style-type: none"> <li>• Require high voltage (~150 MV/m). Recent development allows an order of magnitude less voltage.</li> <li>• Difficult to mass produce</li> <li>• Making thin multilayers is still a challenge and sensitive to defects.</li> <li>• High temperature applications are limited by the Curie temperature</li> </ul>	<ul style="list-style-type: none"> <li>• Electron-radiated P(VDF-TrFE)</li> <li>• P(VDF-TrFE) Terpolymers</li> <li>• P(VDF-TrFE-CTFE) - CTFE disrupts the order in place of the irradiation.</li> </ul>
Dielectric EAP or ESSP	Coulomb forces between the electrodes squeeze the material, causing it to expand in the plane of the electrodes. When the stiffness is low a thin film can be shown to stretch 200-380%.	<ul style="list-style-type: none"> <li>• Large displacements reaching levels of 200–380% strain area</li> <li>• Rapid response (msec levels)</li> <li>• Inexpensive to produce</li> </ul>	<ul style="list-style-type: none"> <li>• Require high voltage (~150 MV/m)</li> <li>• Obtaining large displacements compromises the actuation force</li> <li>• Require prestrain</li> </ul>	<ul style="list-style-type: none"> <li>• Silicone</li> <li>• Polyurethane</li> <li>• Polyacrylate</li> </ul>
Electrostrictive Graft Elastomers	Electric field causes molecular alignment of the pendant group made of graft crystalline elastomers that are attached to the backbone.	<ul style="list-style-type: none"> <li>• Strain levels of 5%</li> <li>• Relatively large force</li> <li>• Cheaper to produce</li> <li>• Rapid response (msec levels)</li> </ul>	<ul style="list-style-type: none"> <li>• Require high voltage (~150 MV/m)</li> </ul>	Copolymer – poly(vinylidene-fluoride-trifluoroethylene)
Liquid Crystal Elastomers [Lehman et al., 2001]	<ul style="list-style-type: none"> <li>• Exhibit spontaneous ferroelectricity</li> <li>• Contracts when heated offering no-electroactive excitation</li> </ul>	<ul style="list-style-type: none"> <li>• When heated it induces large stress and strain (~ 200kPa and 45%, respectively)</li> <li>• Requires much lower field than ferroelectrics &amp; Dielectric EAP (1.5 MV/m, 4 % strain).</li> <li>• Fast response (&lt;133 Hz).</li> </ul>	<ul style="list-style-type: none"> <li>• Low electro-strictive response</li> <li>• Slow response</li> <li>• Hysteresis</li> </ul>	<ul style="list-style-type: none"> <li>• Polyacrylate</li> <li>• Polysiloxane</li> </ul>

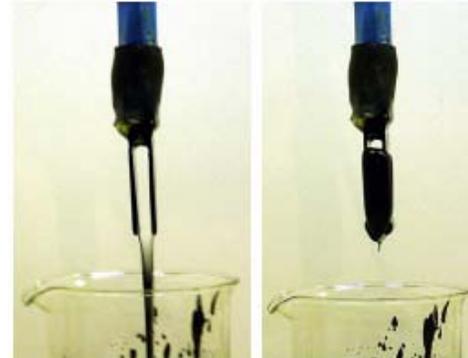
# Ionic EAP

## Turning chemistry to actuation



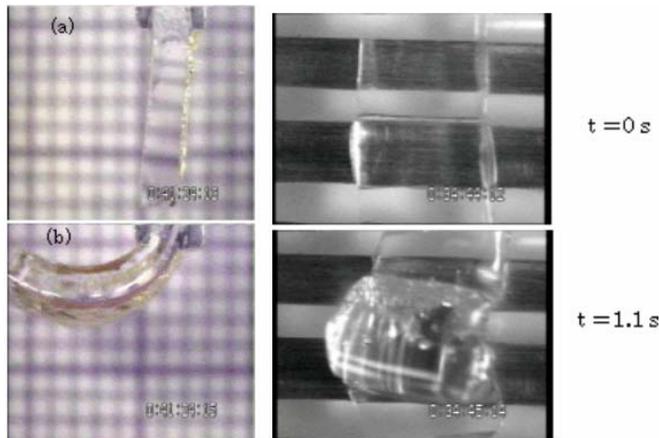
**IPMC**

[JPL using ONRI, Japan & UNM materials]



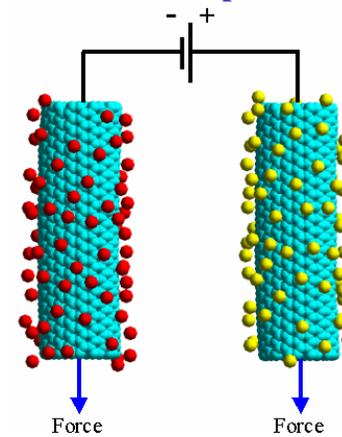
**ElectroRheological Fluids (ERF)**

[ER Fluids Developments Ltd]



**Ionic Gel**

[T. Hirai, Shinshu University, Japan]



**Carbon-Nanotubes**

[R. Baughman et al, Honeywell, et al]

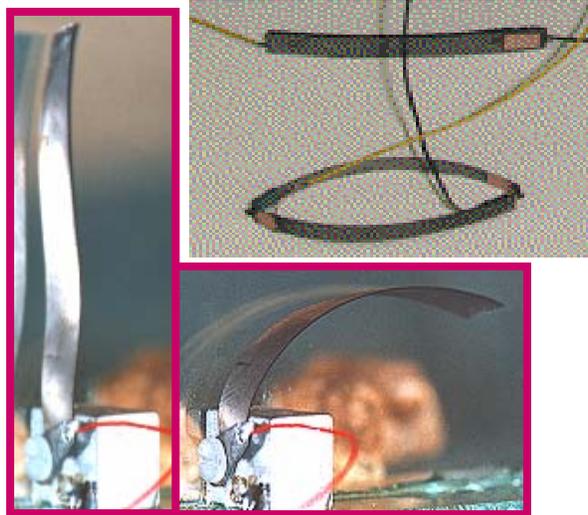
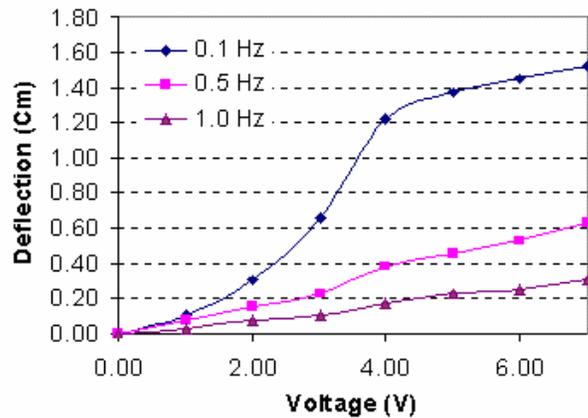
# Ionic EAP

Actuator type	Principle	Advantages	Disadvantages	Reported types
Ionic Gels (IGL)	Application of voltage causes movement of hydrogen ions in or out of the gel. The effect is a simulation of the chemical analogue of reaction with acid and alkaline.	<ul style="list-style-type: none"> <li>Potentially capable of matching the force and energy density of biological muscles</li> <li>Require low voltage</li> </ul>	Operate very slowly—it would require very thin layers and new type of electrodes to become practical	<ul style="list-style-type: none"> <li>Examples include: PAMPS, Poly(vinyl alcohol) gel with dimethyl sulfoxide, and</li> <li>Polyacryl-onitrile (PAN) with conductive fibers</li> </ul>
Ionomeric Polymer-Metal Composites (IPMC)	The base polymer provides channels for mobility of positive ions in a fixed network of negative ions on interconnected clusters. Electrostatic forces and mobile cation are responsible for the bending.	<ul style="list-style-type: none"> <li>Require low voltage (1–5 V)</li> <li>Provide significant bending</li> </ul>	<ul style="list-style-type: none"> <li>Low frequency response (in the range of 1 Hz)</li> <li>Extremely sensitive to dehydration</li> <li>dc causes permanent deformation</li> <li>Subject to hydrolysis above 1.23V</li> <li>Displacement drift under dc voltage.</li> </ul>	Base polymer: <ul style="list-style-type: none"> <li>Nafion® (perfluorosulfonate made by DuPont)</li> <li>Flemion® (perfluorocoboxylate, made by Asahi Glass, Japan)</li> </ul> <b>Cations:</b> <ul style="list-style-type: none"> <li>tetra-n-butylammonium, Li+, and Na+</li> <li>Metal: Pt and Gold</li> </ul>
Conductive Polymers (CP)	Materials that swell in response to an applied voltage as a result of oxidation or reduction, depending on the polarity causing insertion or de-insertion of (possibly solvated) ions.	<ul style="list-style-type: none"> <li>Require relatively low voltage</li> <li>Induce relatively large force</li> <li>Extensive body of knowledge</li> <li>Biologically compatible</li> </ul>	<ul style="list-style-type: none"> <li>Exhibit slow deterioration under cyclic actuation</li> <li>Suffer fatigue after repeated activation.</li> <li>Slow response (&lt;40 Hz)</li> </ul>	Polypyrrole, Polyethylenedioxythiophene, Poly(p-phenylene vinylene)s, Polyaniline, and Polythiophenes.
Carbon Nanotubes (CNT)	The carbon-carbon bond of nanotubes (NT) suspended in an electrolyte changes length as a result of charge injection that affects the ionic charge balance between the NT and the electrolyte.	<ul style="list-style-type: none"> <li>Potentially provide superior work/cycle and mechanical stresses</li> <li>Carbon offers high thermal stability at high temperatures &lt;1000°C</li> </ul>	<ul style="list-style-type: none"> <li>Expensive</li> <li>Difficult to mass produce</li> </ul>	Single- and multi-walled carbon nanotubes
Electrorheological fluids (ERF)	ERFs experience dramatic viscosity change when subjected to electric field causing induced dipole moment in the suspended particles to form chains along the field lines	<ul style="list-style-type: none"> <li>Viscosity control for virtual valves</li> <li>Enable haptic mechanisms with high spatial resolution</li> </ul>	<ul style="list-style-type: none"> <li>Requires high voltage</li> </ul>	Polymer particles in fluorosilicone base oil

# **Application of EAP to potential planetary tasks**

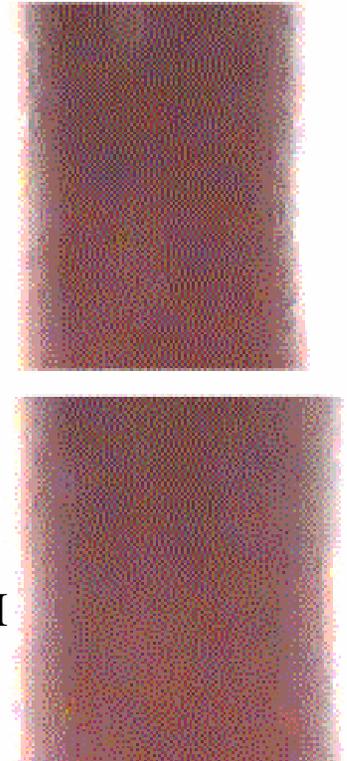
## **Lesson Learned**

# Bending and Longitudinal Actuation



Ionomeric Polymer Metal Composite (IPMC) can **bend** by over  $90^\circ$  under 1-4V.

Dielectric EAP film **extending** over 12%. Recent Studies at SRI International led to ~380% extension.



# Considered planetary applications

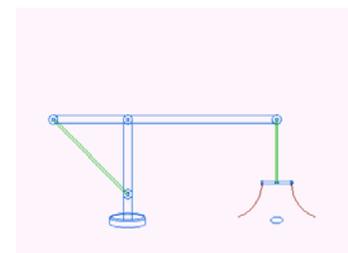
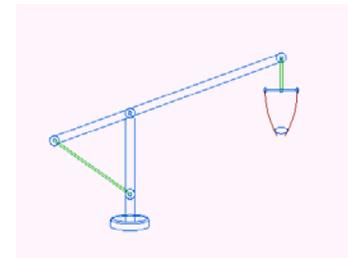
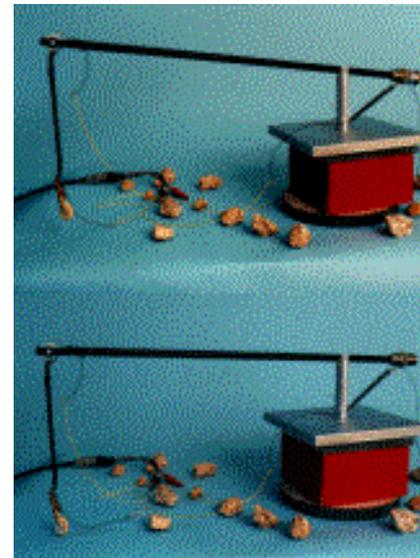
## Dust wiper

Bending EAP is used as a surface wiper



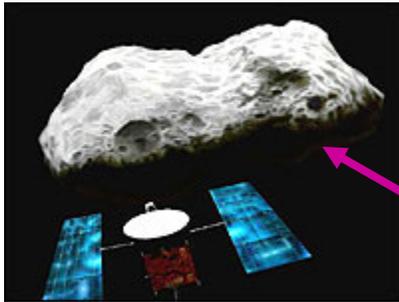
## Sample handling robotics

Extending EAP lowers a robotic arm, while bending EAP fingers operate as a gripper

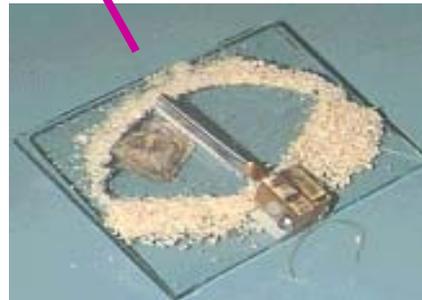
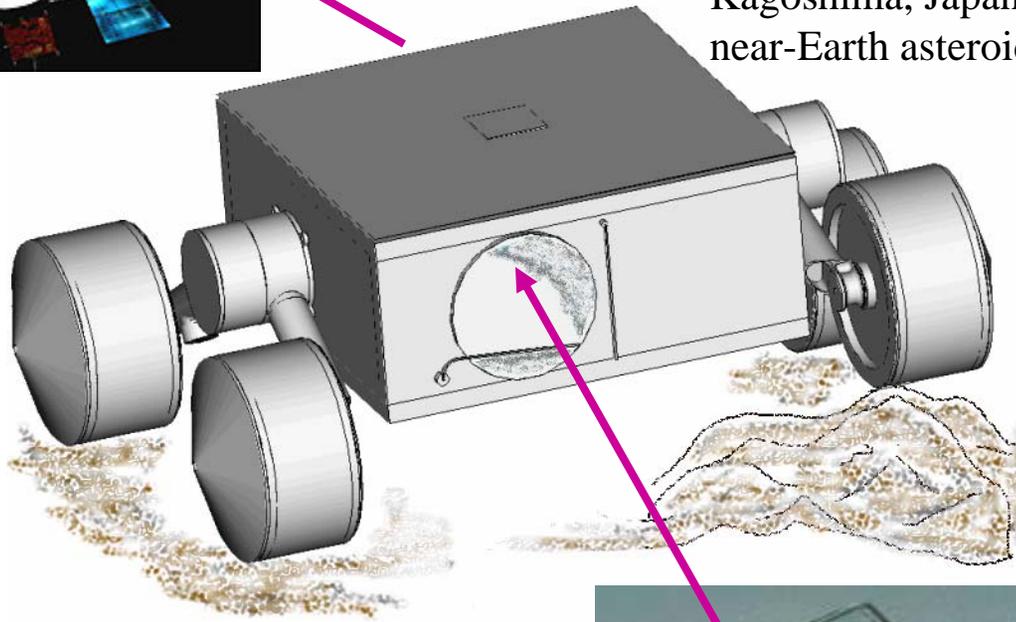


# EAP Dust Wiper

## for the MUSES-CN Nanorover



MUSES-CN mission was a joint NASA and NASDA (National Space Development Agency of Japan) mission scheduled for launch in January 2002, from Kagoshima, Japan, to explore the surface of a small near-Earth asteroid.

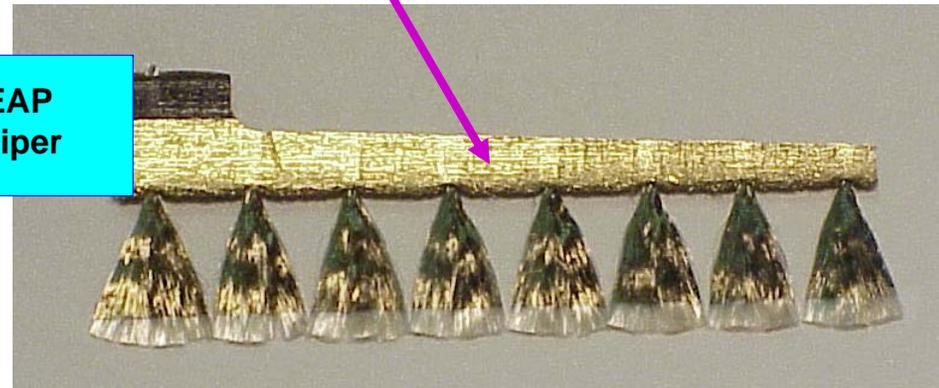


- An IPMC actuated wiper was selected as a baseline for the dust removal from the visual/IR window.
- The technical challenges were beyond the technology readiness requirements
- Due to budget constraints, this mission was cancelled in Nov. 2000.

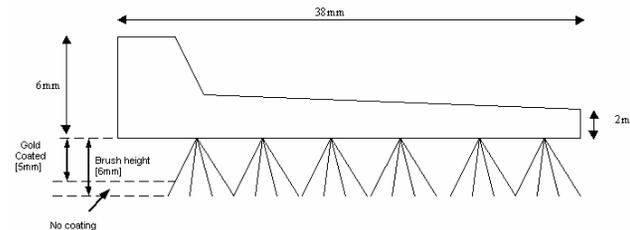
# Surface wiper activated by EAP

Actuated by 1-3 volts

Biased with 1-2KV for dust repulsion



Graphite/Epoxy wiper blade\* with fiberglass brush coated with gold



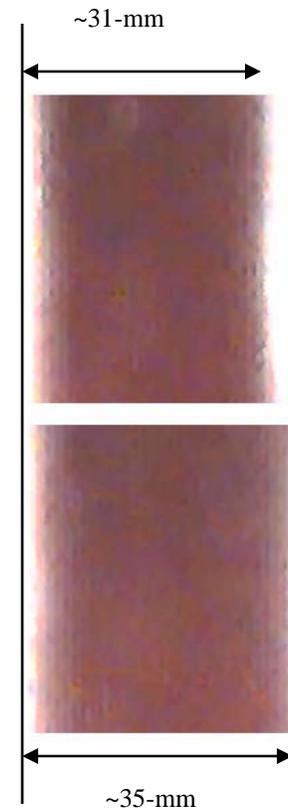
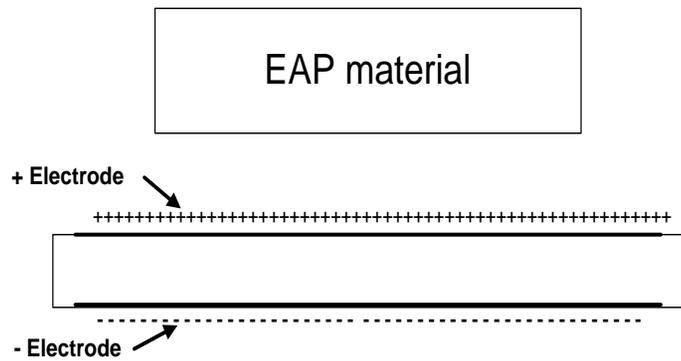
\* Made by Energy Science Laboratories, Inc., San Diego, California

# Challenges and solutions to the application of IPMC as bending actuators

Challenge	Potential Solution
Fluorinate base - difficult to bond	Etching the surface makes it amenable to bonding.
Extremely sensitive to dehydration	Apply protective coating over the etched IPMC.
Off-axis bending actuation	Constrain the free end and use a high ratio of length/width.
Remove submicron dust	Use effective wiper-blade design and high bias voltage.
Reverse bending drift under dc voltage	Limit the operation to cyclic activation to minimize this effect. Also, use large cation based IPMC.
Protective coating is permeable	Develop alternative coating, possibly using multiple layers
Electrolysis occurs at $>1.23$ V	Use efficient IPMC that requires low actuation voltage or use solvent base that exhibits electrolysis at a higher voltage.
Residual deformation particularly after intermittent activation	It occurs mostly after dc activation and it remains a challenge.
Difficulties to assure material reproducibility	Still a challenge. May be overcome using mass production and protective coating.
Degradation with time due to loss of ions to the host liquid if it is immersed	Requires electrolyte with enriched cation content of the same species as in the host liquid.

# LONGITUDINAL EAP ACTUATOR

Under electro-activation, a soft polymer film with electrodes on both surfaces expands laterally.

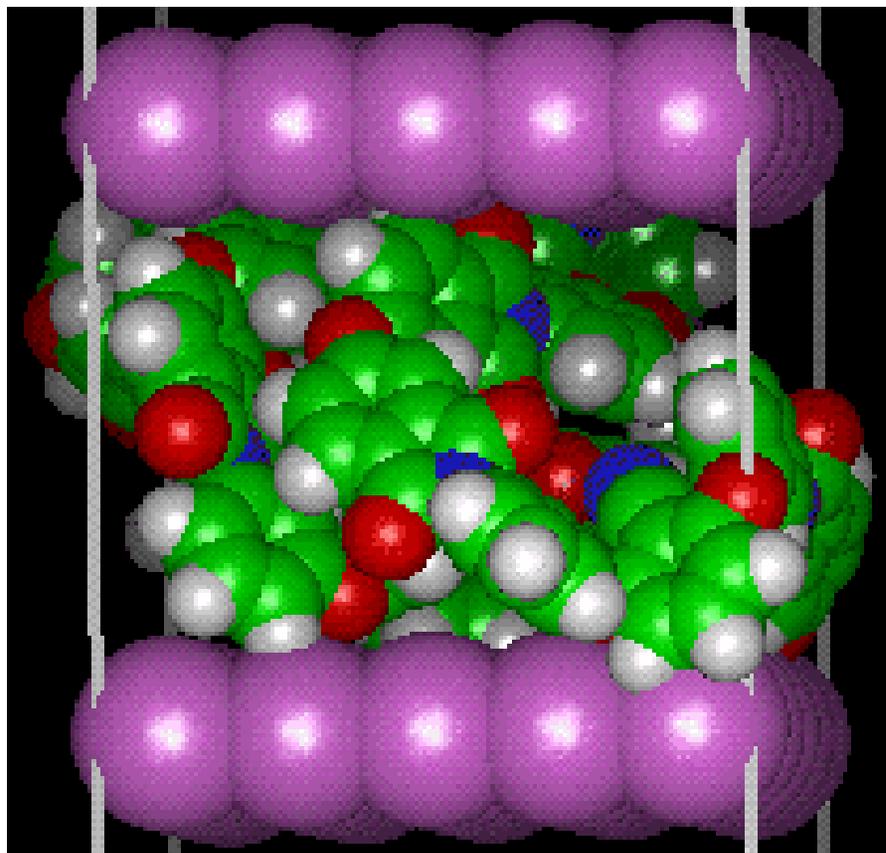


EAP film subjected to  $25 \text{ V}/\mu\text{m}$  induced over 12% extension

# Elements of the EAP Infrastructure

# Computational chemistry

Computational chemistry may lead to material design tools using comprehensive modeling to methodically synthesize effective new EAPs



(NASA-LaRC)

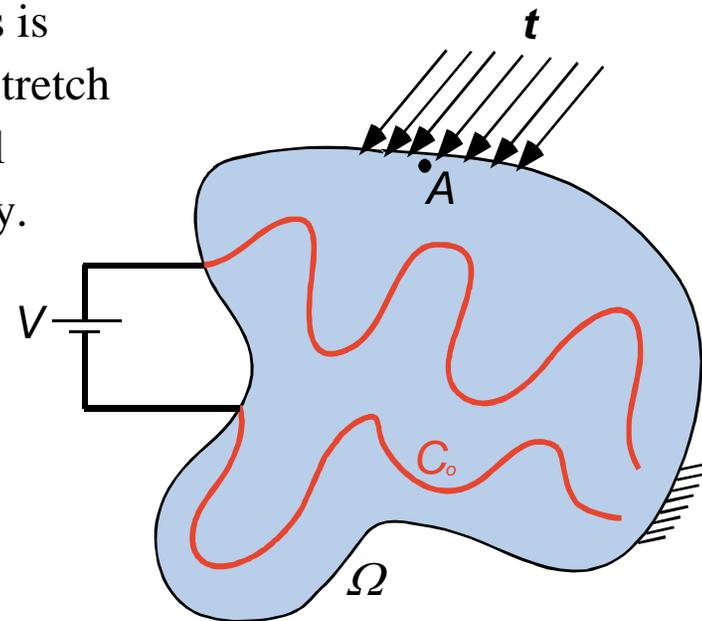
# Modeling EAP addressing their nonlinear behavior

**Objective:** Maximize the stretch in a selected direction among various possible configurations of conductors  $C$  and domains shape  $\Omega$ .

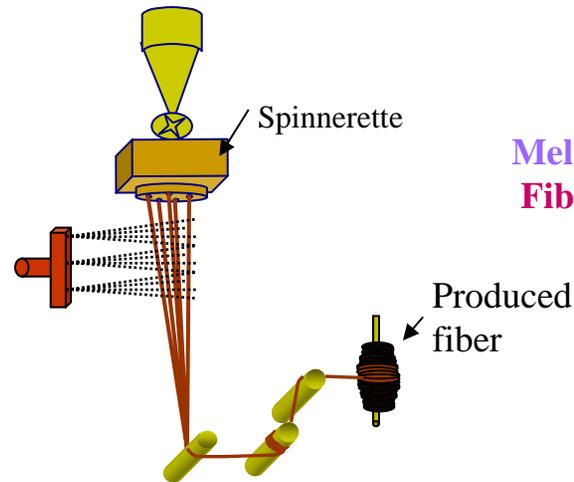
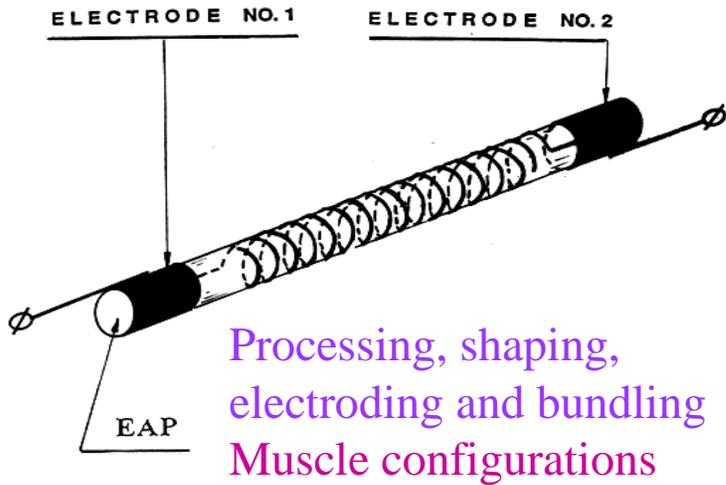
**Constraints:** Some overall geometry of conductors is prescribed ( $C_0$ ), conductors are elastic and the stretch is calculated from a coupled electro-mechanical problem in finite (nonlinear) deformation theory.

## Numerical solution

1. Solve coupled electro-mechanical problem
2. Calculate configurational forces on conductors
3. Change conductor configuration
4. Iterate

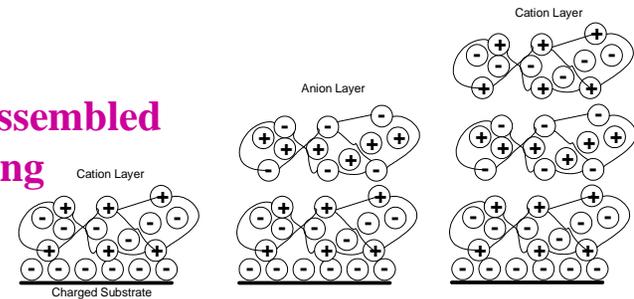


# EAP processing

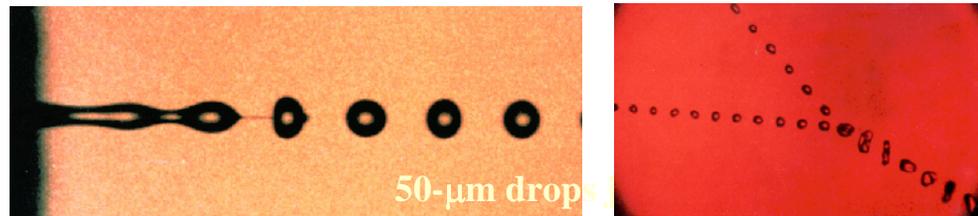


Melt Spinning process  
Fiber fabrication

## Ionic Self-Assembled mono-layering

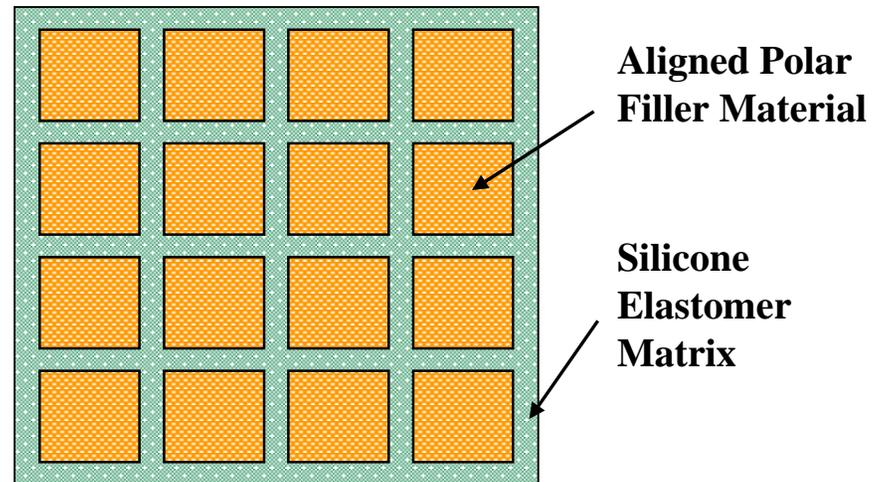


Ink-printing  
Rapid Prototyping using Ink-Jet  
Stereo-lithography and Printing

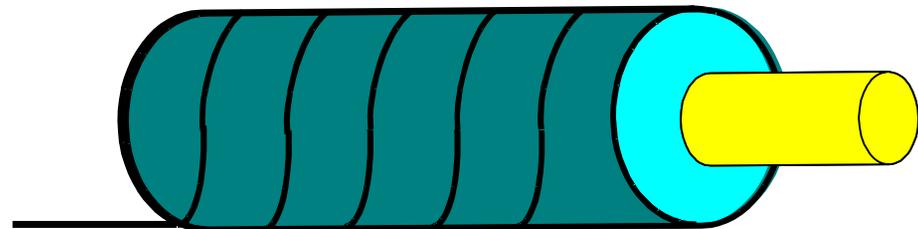


# Composite EAP

**Composite elastomer  
with polarized filler**

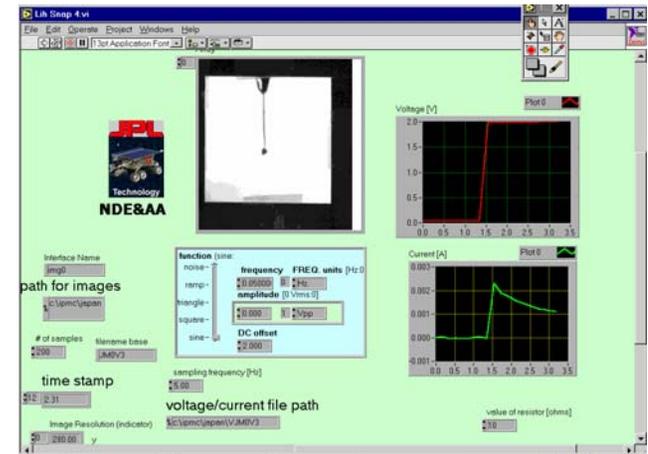
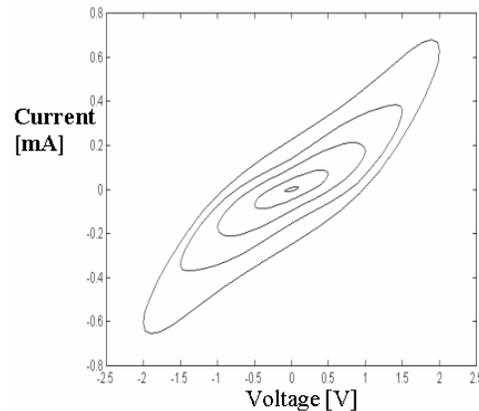
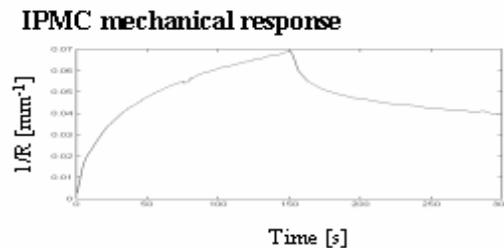
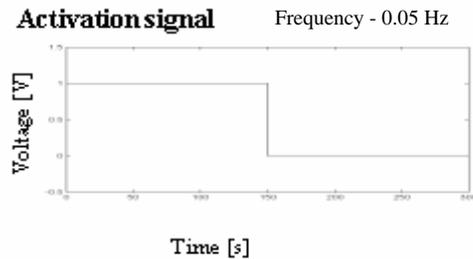
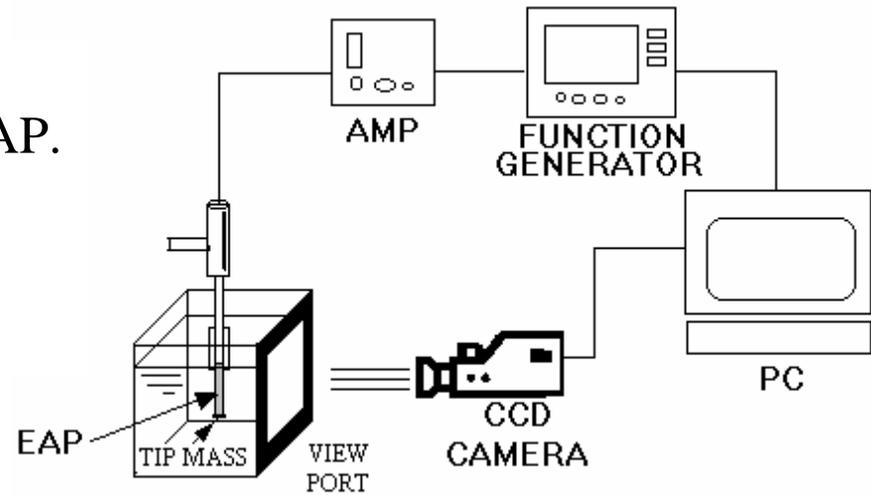


- Cu wire
- Polyaniline fiber
- Solid polymer electrolyte [EC/PC/PAN/Cu(ClO<sub>4</sub>)<sub>2</sub>]



# EAP Material Characterization

- Different methods of characterization are needed for the various types of EAP.
- Efforts are underway to develop a database that allows comparing with properties of other actuators



# Test Metric for EAP Properties

Measurement		Properties	Metric
Mechanical		Tensile strength [Pa]	Mechanical strength of the actuator material
		Stiffness [Pa]	Required to calculate blocking stress, mechanical energy density, and mechanical loss factor/bandwidth
		Coefficient of thermal expansion [ppm/C]	Affects the thermal compatibility and residual stress
Electrical		Dielectric breakdown strength [V]	Necessary to determine limits of safe operation
		Impedance spectra [ohms and phase angle]	Provides both resistance and capacitance data. Used to calculate the electrical energy density; electrical relaxation/dissipation and equivalent circuit.
		Nonlinear current [A]	Used in the calculation of electrical energy density; quantify nonlinear responses/driving limitations
		Sheet resistance [ohms per square]	Used for quality assurance
Microstructure Analysis		Thickness (electrode and EAP), internal structure, uniformity and anisotropy as well as identify defects	These are features that will require establishment of standards to assure the quality of the material
Electro-active Properties	Strain	Electrically induced strain [%] or displacement [cm]	Used in calculation of “blocking stress” and mechanical energy density
	Stress	Electrically induced force [g], or charge (C)	Electrically induced force/torque or stress- induced current density
	Stiffness	Stress/strain curve	Voltage controlled stiffness
Environmental Behavior		Operation at various temperatures, humidity and pressure conditions	Determine material limitations at various conditions

## Significant EAP properties

- Stress (MPa)
- Strain (%)
- Drive voltage (V)
- Bandwidth (Hz) or response rate (sec)
- Power density ( $\text{W}/\text{cm}^3$ )
- Efficiency (%)
- Lifetime (cycles)
- Density ( $\text{g}/\text{cm}^3$ )
- Operating environment (Temperature, pressure, humidity, etc.)

# Potential EAP applications

- EAPs offers unique characteristics to produce highly maneuverable, noiseless, agile biologically-inspired mechanisms.
- EAP can be used to produce actuators that require simple drive signals but their nonlinear behavior needs to be taken into account.
- Developing and applying EAP materials and mechanisms involves interdisciplinary expertise in chemistry, materials science, electronics, mechanisms, computer science and others.
- Robustness and the limited actuation force are constraining the technology

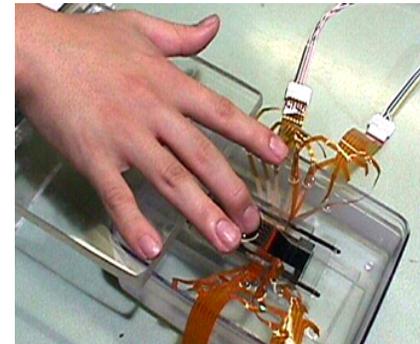
# Applications

## Underway or under consideration

- **Mechanisms**
  - Lenses with controlled configuration
  - Mechanical Lock
  - Noise reduction
  - Flight control surfaces/Jet flow control
  - Anti G-Suit
- **Robotics, Toys and Animatronics**
  - Biologically-inspired Robots
  - Toys and Animatronics
- **Human-Machine Interfaces**
  - Haptic interfaces
  - Tactile interfaces
  - Orientation indicator
  - Smart flight/diving Suits
  - Artificial Nose
  - Braille display (for Blind Persons)
- **Planetary Applications**
  - Sensor cleaner/wiper
  - Shape control of gossamer structures
- **Medical Applications**
  - EAP for Biological Muscle Augmentation or Replacement
  - Miniature in-Vivo EAP Robots for Diagnostics and Microsurgery
  - Catheter Steering Mechanism
  - Tissues Growth Engineering
  - Interfacing Neuron to Electronic Devices Using EAP
  - Active Bandage
- **Liquid and Gases Flow Control**
- **Controlled Weaving**
  - Garment and Clothing
- **MEMS**
- **EM Polymer Sensors & Transducers**

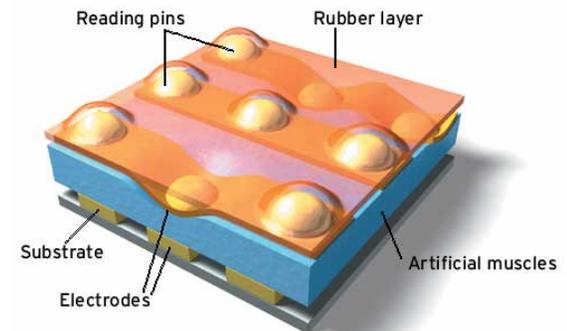
# Human-Machine Interfaces

- Interfacing human and machine to complement or substitute our senses would enable important medical applications.
- Researchers at Duke U. connected electrodes to a brain of a monkey and were able to control a robotic arm. This breakthrough opens the possibility that the human brain would be able to operate prosthetics that are driven by EAP.
- Feedback is required to “feel” the environment around the artificial limbs. Currently, researchers are developing tactile sensors, haptic devices, and other interfaces.



**Tactile Interface**

(S. Tadokoro, Kobe U., Japan)



**Active Braille Display**

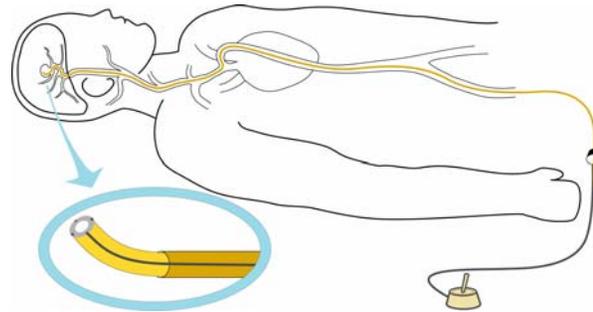
# Medical Applications



## Cyborgs potentials for EAP actuators

G. Whiteley, Sheffield Hallam U., UK

- EAP for Augmentation or Replacement of biological Muscle
- Miniature in-Vivo EAP Robots for Diagnostics and Microsurgery
- Catheter Steering Mechanism
- Tissues Growth Engineering
- Interfacing Neuron to Electronic Devices Using EAP
- Active Bandage



## Catheter Guide Using IPMC

K. Oguro, ONRI, Japan

## EAP based microanastomosis connector

Micromuscle, Sweden



Smart pill that can crawl inside the gastronomical track



An EAP Braille display being tested by a blind person

Choi, et al, Sungkyunkwan University, Korea, 2004

# Exploration of planetary applications

## Dust wiper

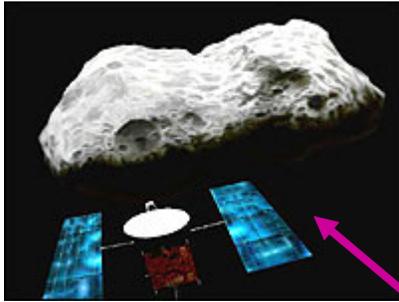


## Sample handling robotics

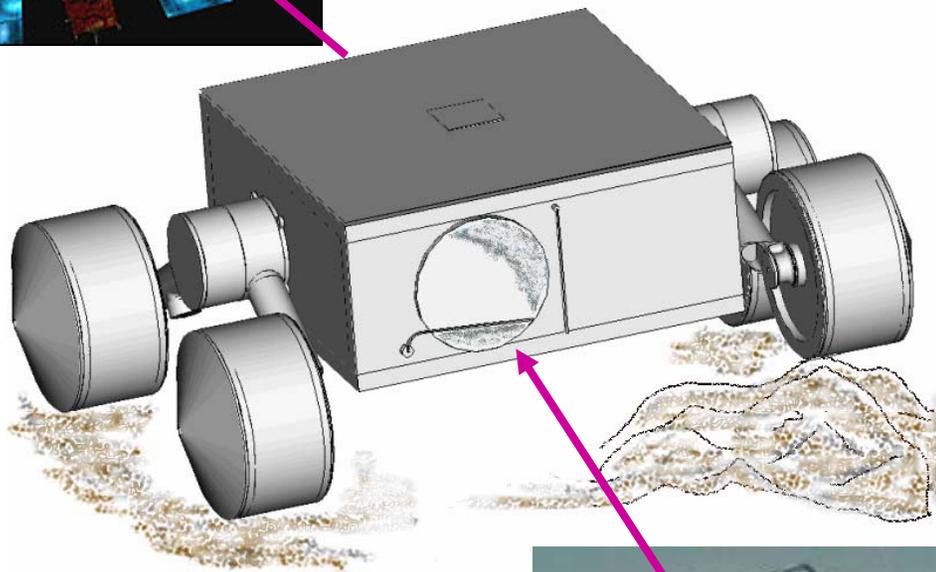


# EAP dust wiper

## Baselined in the MUSES-CN Nanorover

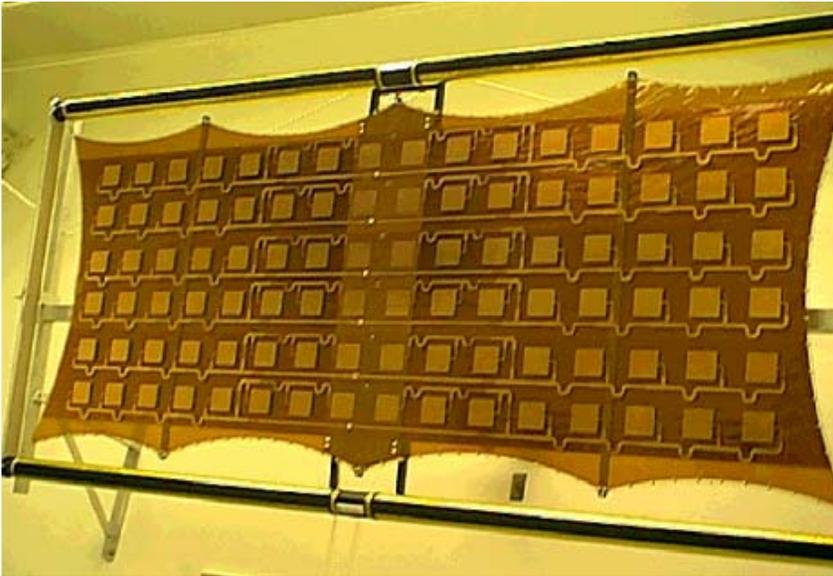


MUSES-CN mission was a joint NASA and NASDA (National Space Development Agency of Japan) mission scheduled for launch in Jan. 2002, from Kagoshima, Japan, to explore the surface of a small near-Earth asteroid. Due to budget constraints, this mission was cancelled in Nov. 2000.



- An IPMC actuated wiper was selected as a baseline for the dust removal from the visual/IR window.
- The technical challenges were beyond the technology readiness requirements

# Large space structures



Inflatable and rigidized Synthetic Aperture Radar at JPL.



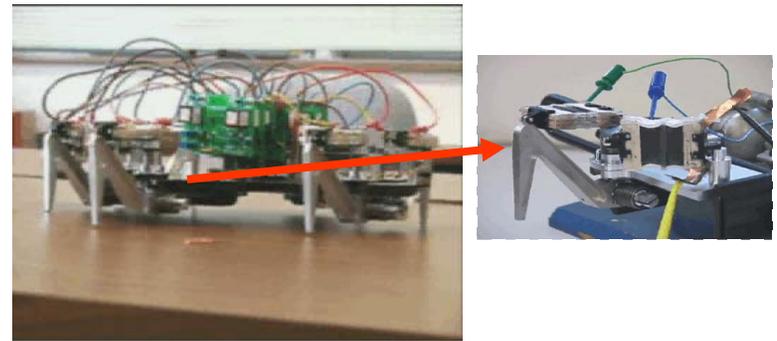
Space Shuttle view of the L'Garde's Inflatable Antenna Experiment (IAE)

# Robotics, Toys and Animatronics

Biologically inspired robotics and rapid inexpensive mechanisms are highly attractive and offer novel possibilities that might be considered otherwise science fiction.

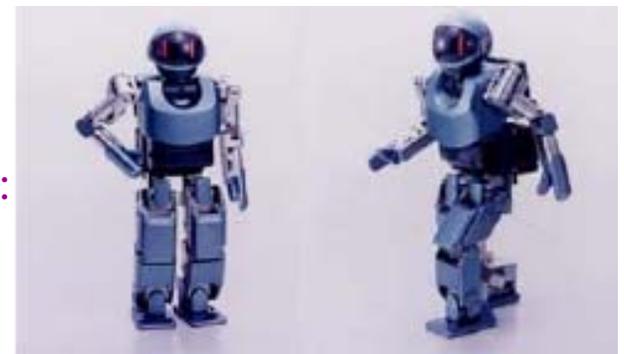


Android making facial expressions  
(G. Pioggia et al. U. of Pisa, Italy)



Hexapod robot powered by dielectric EAP (R. Kornbluh, et al., SRI International)

Desired capability:

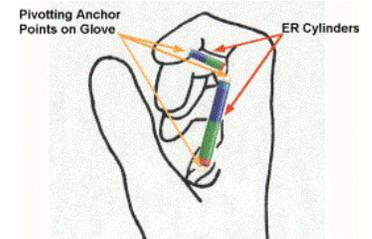
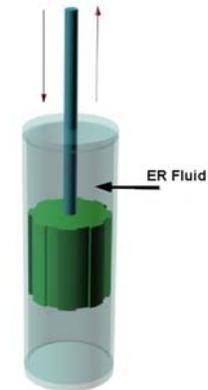
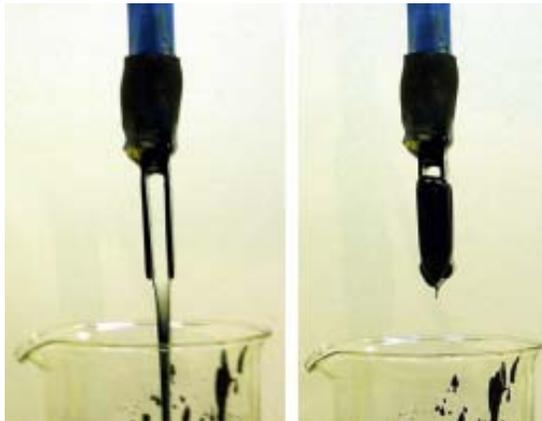
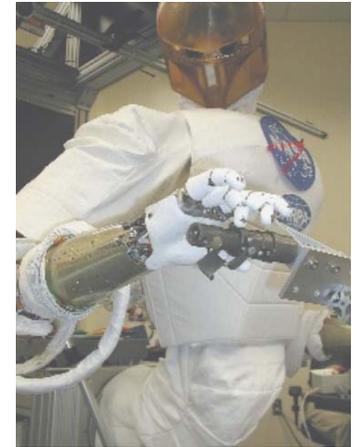
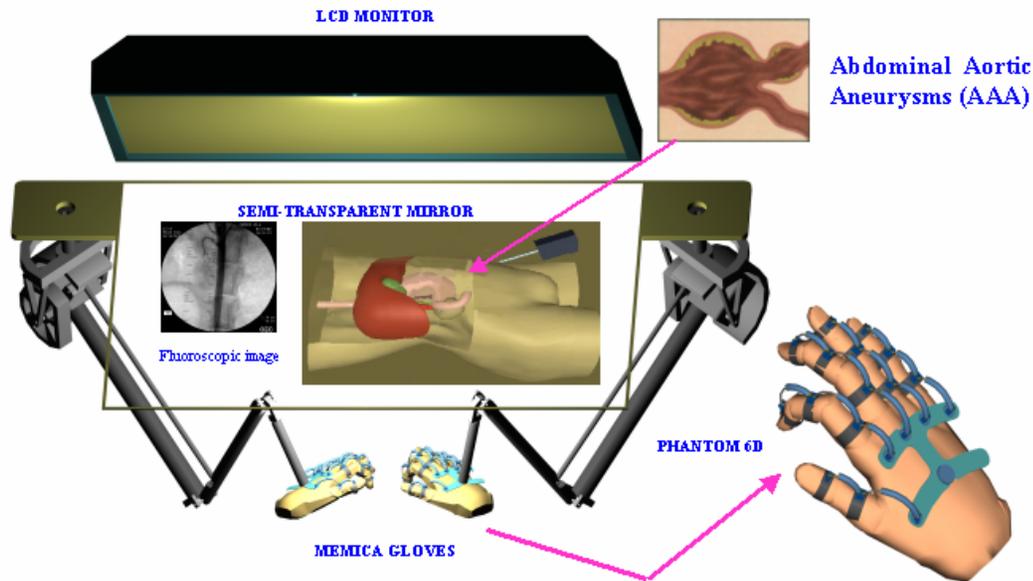


Sony's SDR3

YB-40

# MEMICA

(MEchanical Mirroring using Controlled stiffness and Actuators)



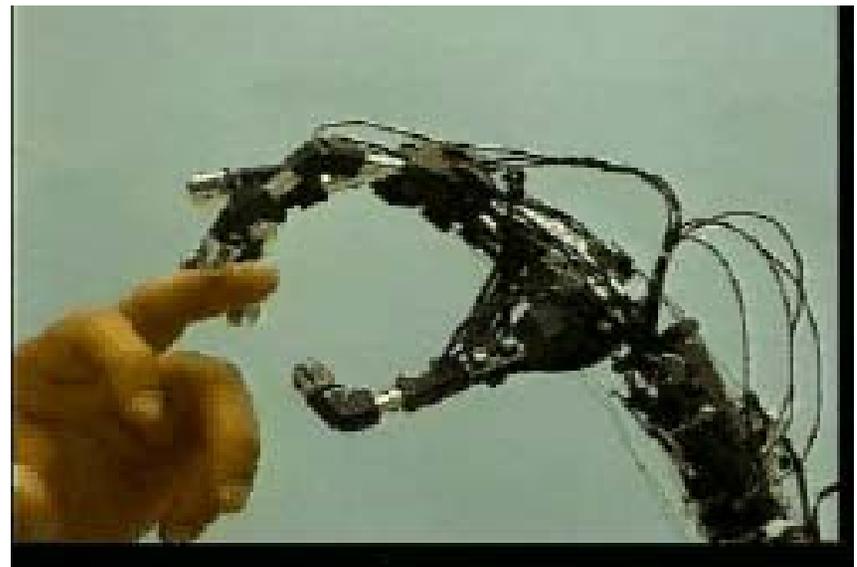
Electro-Rheological Fluid at reference (left) and activated states (right). [Smart Technology Ltd, UK]

# Platforms for EAP Implementation



**Android making facial expressions**

[Made by D. Hanson, U. of Texas, Dallas]



**Robotic hand platform for EAP**

[Made by G. Whiteley, Sheffield Hallam U., UK]

# BIOLOGICALLY INSPIRED ROBOTS

Potential use for in-situ scalable autonomous robots in colonized multi-tasking exploration

## Models for EAP actuated flexible robots

### Multiple locomotion capabilities

Flying,  
walking,  
swimming &  
diving



Hopping,  
flying,  
crawling  
& digging



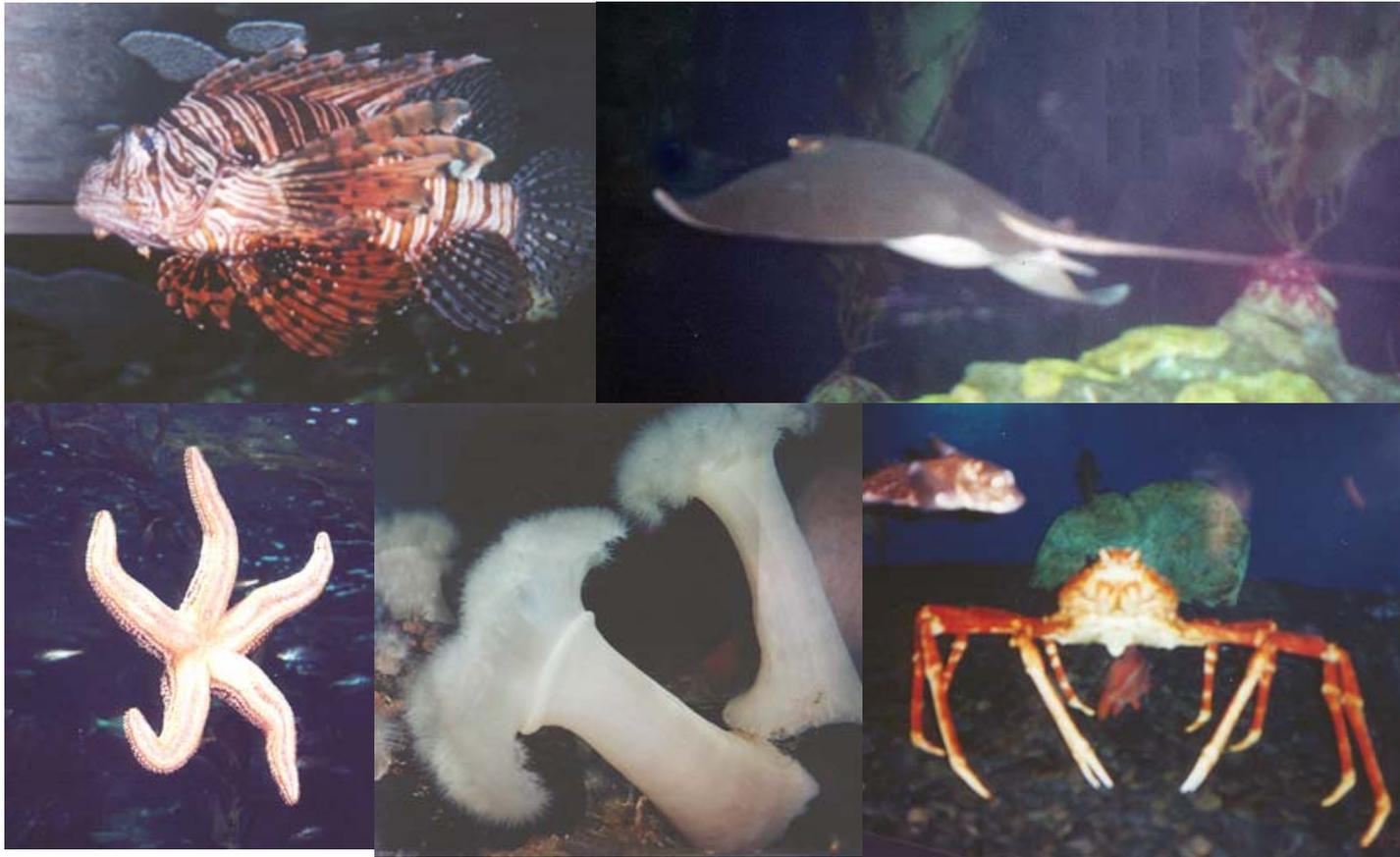
### Coordinated robotics

Neural networks  
& expert systems

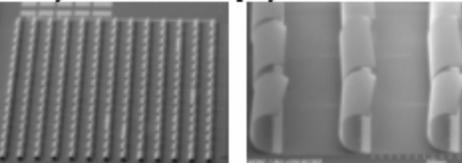


# A challenge to EAP

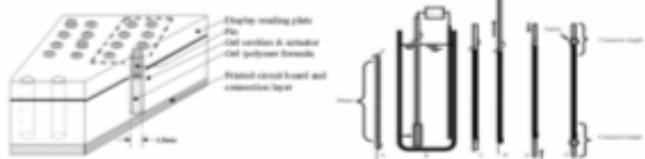
## Emulating sea creatures



# EAP material and product manufacturers

Company Name, Contact person, E-mail, Website	EAP materials/processes/products
<p><b>Artificial Muscle, Inc.</b> (AMI)* 333 Ravenswood Ave., Menlo Park, CA 94025 <i>Artificial Muscle Inc</i></p>  <p>Alex N. Beavers, Jr., Ph.D. Chief Executive Officer; <a href="mailto:alex@artificialmuscle.com">alex@artificialmuscle.com</a> <a href="http://www.artificialmuscle.com">www.artificialmuscle.com</a> *Founded by SRI International</p>	<ul style="list-style-type: none"> <li>Design and manufacture EAP based solid state actuators, sensors, and generator components for automotive, industrial machinery and automation, electronics, consumer goods, medical, and aerospace.</li> <li>EAP devices including valve controllers, pumps, electric servo motor replacement, force and pressure sensors, acoustic speakers, and linear position actuators.</li> </ul> 
<p><b>EAMEX Corporation</b> 5-16-608 Uhocyou, Ikeda city, Osaka, Japan</p>  <p>Shingo Sewa or Kazuo Onishi; <a href="mailto:web@eamex.co.jp">web@eamex.co.jp</a>; <a href="http://www.eamex.co.jp/index_e.html">http://www.eamex.co.jp/index_e.html</a></p>	<ul style="list-style-type: none"> <li>Conductive polymer EAP and IPMC actuators</li> <li>EAP actuators for medical applications (nursing equipment, catheter, guide wires, and rehabilitation instrument); robotics; industry (manipulator and conveyance equipment); hobby and art, as well as customized EAP products</li> </ul>  <p>EAP based hand</p>
<p><b>Environmental Robots Incorporated</b> 909 Virginia, NE., Suite 205, Albuquerque, New Mexico 87108, USA</p>  <p>Mohsen Shahinpoor or Massoud Ahghar; <a href="mailto:shah@environmental-robots.com">shah@environmental-robots.com</a> or <a href="mailto:mahghar@environmental-robots.com">mahghar@environmental-robots.com</a>; <a href="http://www.environmental-robots.com">www.environmental-robots.com</a></p>	<ul style="list-style-type: none"> <li>IPMC-based and ionic polymer actuators, transducers, and sensors</li> <li>IPMC and conductive polymer EAP for biomedical engineering and medical applications</li> <li>Kits of bending and contractile EAP, ionic polymeric fiber bundles, conductive polymers and chemically activated polymers</li> </ul>  <p>IPMC</p>
<p><b>MCNC Research and Development Institute</b></p>  <p>Scott Goodwin, <a href="mailto:goodwin@mcnc.org">goodwin@mcnc.org</a>, <a href="http://www.mcnc.org/rdi/">http://www.mcnc.org/rdi/</a></p>	<p>Dielectric EAP device development and prototyping of</p> <ul style="list-style-type: none"> <li>"Artificial Eyelid" polymer flexible film</li> <li>Electrostatic MEMS actuator</li> <li>Integrated force array and electrostatic polymer actuator</li> </ul>  <p>Artificial Eyelid</p>

# EAP material and product manufacturers

<p><b>Micromuscle AB</b> Westmansgatan 29, 582 16 Linköping, Sweden,</p>  <p>Edwin Jager, CTO, <a href="mailto:edwin.jager@micromuscle.com">edwin.jager@micromuscle.com</a>; Gert Kindgren, CEO, <a href="mailto:gert.kindgren@micromuscle.com">gert.kindgren@micromuscle.com</a>; <a href="http://www.micromuscle.com">www.micromuscle.com</a></p>	<ul style="list-style-type: none"> <li>EAP Products include materials and devices ranging from cellular levels for lab-on-a-chip to implantation in the human body.</li> <li>Conductive polymers EAP actuators ranging in size from micrometers to several centimeters.</li> <li>Components and devices for medical devices, vascular surgery, MEMS and biomedicine micro-systems.</li> </ul>   
<p><b>Molecular Mechanisms LLC</b></p>  <p>Customer Support, <a href="mailto:sales@molecularmechnisms.com">sales@molecularmechnisms.com</a>, <a href="http://www.molecularmechnisms.com">www.molecularmechnisms.com</a></p>	<ul style="list-style-type: none"> <li>Development of EAP based mechanisms</li> <li>Polypyrrole (PPy) tapes for Conductive Polymers (CP) EAP</li> </ul>  <p>Bilayer CP EAP activated in air</p>
<p><b>NanoSonic, Inc.</b> 1485 S. Main Street Blacksburg, VA 24060</p>  <p>Richard O. Claus, President, <a href="mailto:info@nanosonic.com">info@nanosonic.com</a>; <a href="http://www.nanosonic.com">http://www.nanosonic.com</a></p>	<ul style="list-style-type: none"> <li>Low modulus sensors for strain, vibration and fluid flow</li> <li>Free-standing conductive and reflective elastomeric membranes</li> <li>Flexible electroding for EAP actuators using modified self-assembly (demonstrated for dielectric EAP)</li> </ul>  <p>Stretchable electroding material</p>
<p><b>Quantum Technology Pty. Ltd.</b> 5 South Street, Rydalmere, N.S.W. 2126, Australia</p>  <p>Tim Connell <a href="mailto:tconnell@quantech.com.au">tconnell@quantech.com.au</a> <a href="http://www.quantech.com.au/">http://www.quantech.com.au/</a></p>	<ul style="list-style-type: none"> <li>Development of EAP actuators for Braille Cells as an aid to visually impaired and blind.</li> </ul> 
<p><b>SRI International*</b> 333 Ravenswood Avenue, Menlo Park, CA 94025</p>  <p>Philip von Cuggenberg, Director of Business Development, <a href="mailto:pvong@sri.com">pvong@sri.com</a>, <a href="http://www.sri.com/artificialmuscle">www.sri.com/artificialmuscle</a></p> <p>* In 2003, AMI was found to commercialize the EAP technology</p>	<ul style="list-style-type: none"> <li>Dielectric EAP actuators</li> <li>Devices and mechanisms that are driven by dielectric EAP</li> <li>R&amp;D contracts to explore and extend the application of EAP technologies to scientific, industrial, and military environments from nano to mega scale devices.</li> </ul>   <p>Dielectric EAP</p> <p>Voltage Off      Voltage On</p>

# Concerns and requirements

- No established database or standard test procedures
- Applications are needed where the specifications are within the EAP capability range
- Robustness – there are lifetime and reliability issues
- Scalability – it is not obvious how to make very large or very small EAP
- Competitiveness – there is a need for niche applications

## SPIE Conference - EAPAD

To accelerate the development of EAP actuators an SPIE International Conference and a committee were initiated in 1998 to serve as a forum for collaboration among the developers and users of the technology.

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### Technical Conference

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**Conference 4329**  
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*Proceedings of SPIE* Vol. 4329

## Electro-Active Polymer Actuators and Devices

*Conference Chair:* **Yoseph Bar-Cohen**, Jet Propulsion Lab.

*Cochair:* **Danilo De Rossi**, Univ. degli Studi di Pisa (Italy)

*Program Committee:* **Ray H. Baughman**, AlliedSignal Inc.; **Paul D. Calvert**, Univ. of Arizona; **Richard O. Claus**, Virginia Polytechnic Institute and State Univ.; **Michael Goldfarb**, Vanderbilt Univ.; **Joycelyn S. Harrison**, NASA Langley Research Ctr.; **Roy D. Kombluh**, SRI International; **Chang Liu**, Univ. of Illinois/Urbana-Champaign; **Ajit K. Mal**, Univ. of California/Los Angeles; **Benjamin R. Mattes**, Santa Fe Science and Technology Inc.; **Siavouche Nemat-Nasser**, Univ. of California/San Diego; **Keisuke Oguro**, Osaka National Research Institute (Japan); **Yoshihito Osada**, Hokkaido Univ. (Japan); **Toribio F. Otero**, Univ. del País Vasco (Spain); **Randall R. Sands**, Consultant; **Mohsen Shahinpoor**, Univ. of New Mexico and Environmental Robots, Inc.; **Valery P. Shibaev**, Moscow State Univ. (Russia); **Peter Sommer-Larsen**, Risø National Lab. (Denmark); **Minoru Taya**, Univ. of Washington; **Gordon G. Wallace**, Univ. of Wollongong (Australia); **Steven G. Wax**, DARPA; **Qiming Zhang**, The Pennsylvania State Univ.; **Miklos Zrinyi**, Technical Univ. of Budapest (Hungary)

## Recent News

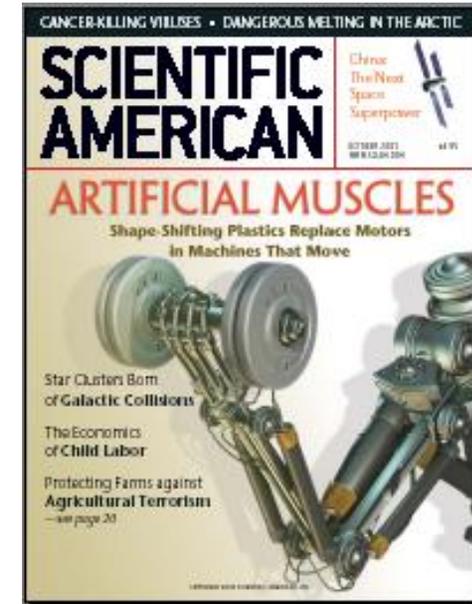
Dec. 2002- The first commercial EAP product - a fish robot (courtesy of Eamex, Japan)



Multifunctional Electroelastomer Roll (MER) Spring Roll (courtesy of SRI International)



A wrestling arm driven by polyacrylonitrile (PAN-C) EAP (Courtesy of M. Shahinpoor, U. of New Mexico and Environmental Robots Incorporated (ERI), New Mexico)



Cover page of the Oct. 2003 issue



YB-49

# SUMMARY

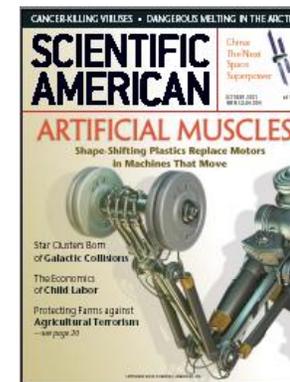
- Electroactive Polymers have emerged as actuators for generating large displacements
- These materials offer the closest resemblance of biological muscles potentially enabling unique capabilities
- In recognition of the EAP limitation a series of international forums were established including conferences [SPIE (March) and MRS (Dec. every two years)], Webhub, Newsletter, and Newsgroup.
- Significant advances are increasingly being reported in each area of the EAP infrastructure including improved understanding of their mechanisms, increased performance and robustness, better test methods, etc.
- A challenge was posed to the EAP community to have an arm wrestling between robot that is equipped with EAP actuators and human. The first competition will be held in this EAPAD Conference.

# WW-EAP Homepages

**Links from the Webhub:** <http://ndea.jpl.nasa.gov/nasa-nde/lommas/eap/EAP-web.htm>

- **Books and Proceedings:** <http://ndea.jpl.nasa.gov/nasa-nde/yosi/yosi-books.htm>
- **WW-EAP Newsletter** <http://ndea.jpl.nasa.gov/nasa-nde/lommas/eap/WW-EAP-Newsletter.html>
- **EAP Recipes:** EAP preparation processes  
<http://ndea.jpl.nasa.gov/nasa-nde/lommas/eap/EAP-recipe.htm>
- **EAP in Action Videos:** Short videos showing various EAP materials and mechanisms being activated  
<http://ndea.jpl.nasa.gov/nasa-nde/lommas/EAP-video/EAP-videos.html>
- **EAP Database:** A table of EAP properties with a disclaimer  
<http://ndea.jpl.nasa.gov/nasa-nde/lommas/eap/actuators-comp.pdf>
- **EAP Companies:** A list of EAP manufacturers  
<http://ndea.jpl.nasa.gov/nasa-nde/lommas/eap/EAP-material-n-products.htm>

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## Books

- Bar-Cohen Y. (Ed.), “Electroactive Polymer (EAP) Actuators as Artificial Muscles - Reality, Potential and Challenges,” SPIE Press, <http://www.spie.org/bookstore/> 1st Edition, ISBN: 081944054X (2001) pp. 1-687 and 2nd Edition (March 2004).

## Proceedings

SPIE - Y. Bar-Cohen (Editor)

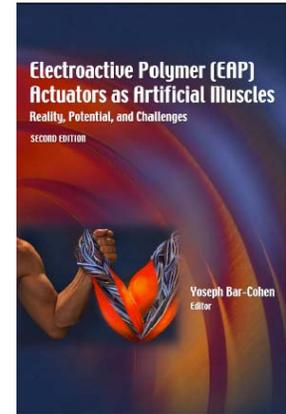
- "ElectroActive Polymer Actuators and Devices (EAPAD)," Proceedings of the SPIE's 6th Annual International Symposium on Smart Structures and Materials, Vol. 3669, ISBN 0-8194-3143-5, (1999), pp. 1-414
- Proceedings of the SPIE’s EAPAD Conf., 7th Smart Structures and Materials Symposium, Vol. 3987, ISBN 0-8194-3605-4 (2000), pp 1-360.
- Proceedings of the SPIE’s EAPAD Conf., 8th Smart Structures and Materials Symposium, Vol. 4329, ISBN 0-8194-4015-9 (2001), pp. 1-524.
  - Proceedings of the SPIE’s EAPAD Conf., 9th Smart Structures and Materials Symposium, Vol. 4695, ISBN 0-8194-4443-X (2002). pp. 1-506.
  - Proceedings of the SPIE’s EAPAD Conf., 10th Smart Structures and Materials Symposium, Vol. 5051, ISBN 0-8194-4856-7 (2003), pp. 1-556.
  - Proceedings of the SPIE’s EAPAD Conf., 11th Smart Structures and Materials Symposium, Vol. 5385, ISBN 0-8194-5302-1 (2004) , pp. 1-572.

## MRS

- Q.M. Zhang, T. Furukawa, Y. Bar-Cohen, and J. Scheinbeim (Eds), “Electroactive Polymers (EAP),” ISBN 1-55899-508-0, 1999 MRS Symposium Proceedings, Vol. 600, Warrendale, PA, (2001), pp 1-336.
- Y. Bar-Cohen, Q.M. Zhang, E. Fukada, S. Bauer, D. B. Chrisey, and S. C. Danorth (Eds), “Electroactive Polymers (EAP) and Rapid Prototyping,” ISBN 1-55899-634-6, 2001 MRS Symposium Proceedings, Vol. 698, Warrendale, PA, (2002), pp 1-359.

# Book about EAP

## Y. Bar-Cohen (Ed.), 2<sup>nd</sup> Edition, SPIE Press, 2004



### Topic 1: Introduction

- Chapter 1.0 - History, Current Status and Infrastructure – Y. Bar-Cohen, JPL

### Topic 2: Natural Muscles

- Chapter 2.0 - Natural Muscles as a Biological system – G. Pollack, et al., U. of Washington
- Chapter 3.0 - Natural Muscles as an Electromechanical System – R. J. Full and K. Meijer, U. of California, Berkeley

### Topic 3: EAP Materials

- *SubTopic 3.1 Electric EAP*
  - Chapter 4.0 - Electric Field Activated EAP – Qiming Zhang, Cheng Huang, and Feng Xia  
– The Pennsylvania State University
- *SubTopic 3.2 Ionic EAP*
  - Chapter 5.0 - Electroactive Polymer Gels – P. Calvert, UA
  - Chapter 6.0 - Ionic Polymer-Metal Composite (IPMC) – S. Nemat-Nasser, and C. Thomas UCSD
  - Chapter 7.0 - Conductive Polymers (CP) – J. Sansiñena, and V. Olazabal, JPL
  - Chapter 8.0 - Carbon Nanotube Actuators – G. Spinks, G. Wallace and U. of Wollongong, Australia, R. Baughman, Honeywell and L. Dai, CSIRO
- *SubTopic 3.3 Molecular EAP*
  - Chapter 9.0 - Micro, Nano and molecular scale EAP – M. Marsella, UCR

### Topic 4: Modeling Electroactive Polymers

- Chapter 10.0 - Computational Chemistry – K. E. Wise, NRC, NASA LaRC
- Chapter 11.0 - Modeling and Analysis of the Chemistry and Electromechanics – T. Wallmersperger, B. Kroeplin - University of Stuttgart, Germany, and R. W. Guelch, University of Tuebingen
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# Book about EAP

Y. Bar-Cohen (Ed.), 2<sup>nd</sup> Edition, SPIE Press, 2004

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- Chapter 14.0 - Processing and Support Techniques -- Y. Bar-Cohen, V. Olazabal, JPL, J. Sansiñena, JPL, and J. Hinkley, NASA LaRC

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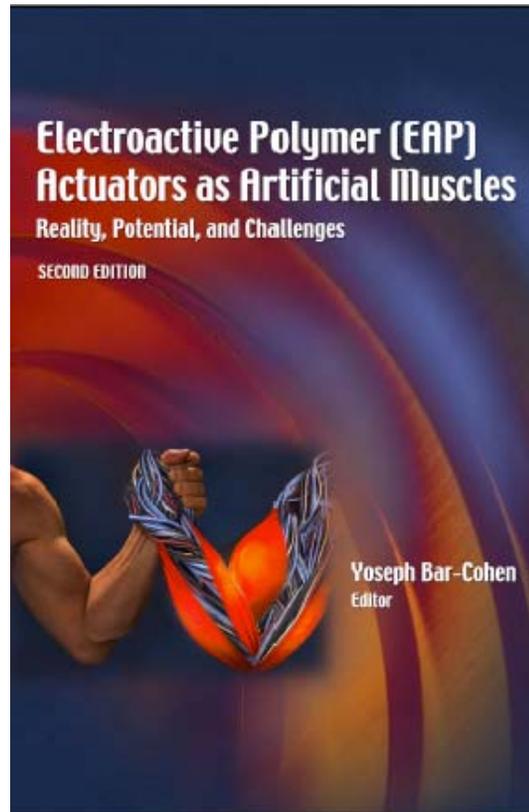
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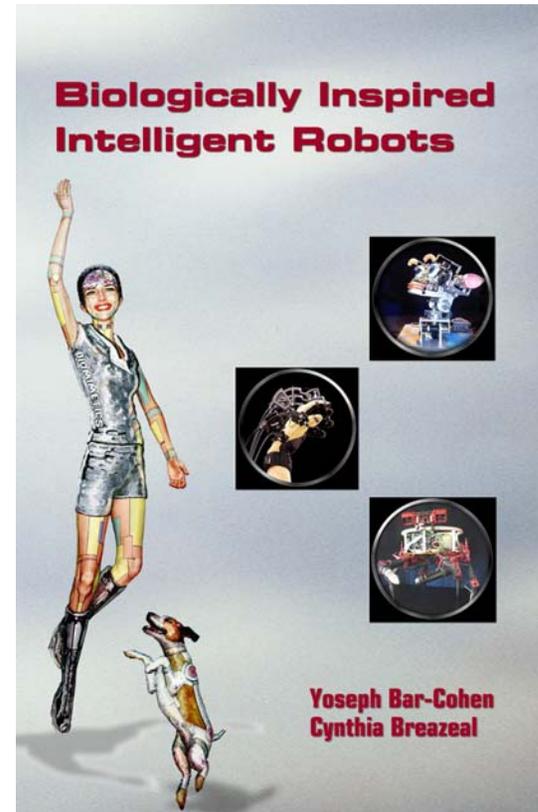
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