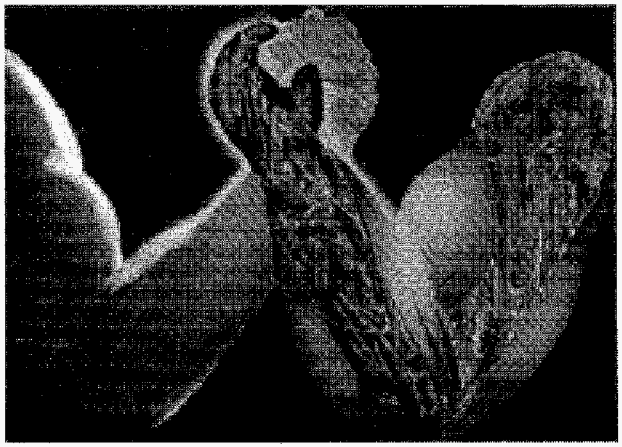
ELECTROACTIVE POLYMERS AS ARTIFICIAL MUSCLES – *REALITY, POTENTIAL AND CHALLENGES*



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SPIE Course on EAPAD

March 4, 2001, Newport Beach, California

Outline

- EAP background and what are the alternative
- Electroactive polymers as artificial muscles
- What are the currently available EAP materials and their properties?
- EAP application considerations
- Future development and applications

What is an Electroactive Polymer (EAP)

- EAP materials are polymers that exhibit change in a property or a material/physical characteristic as a result of an electrical stimulation (field, current, etc.).
- Changes can involve physical deformation, optical or magnetic variation and others.
- The emphasis of this course is on EAP materials that display electro-mechanical reaction.

Background and motivation

- Conventional robots are driven by mechanisms that consist of motors, gears, bearings, etc.
- Emulating biological muscles can enable robotics and various manipulation capabilities that are impossible today.
- Electroactive polymers (EAP) are emerging with capability that can mimic muscles.
- EAP are resilient, fracture tolerant, noiseless actuators that can be made miniature, low mass, inexpensive and consume low power.
- Robotic devices can be made of materials only, serving as the structure and the actuators. Using inkjet printing one can rapidly prototype 3-D systems.

Historical prospective

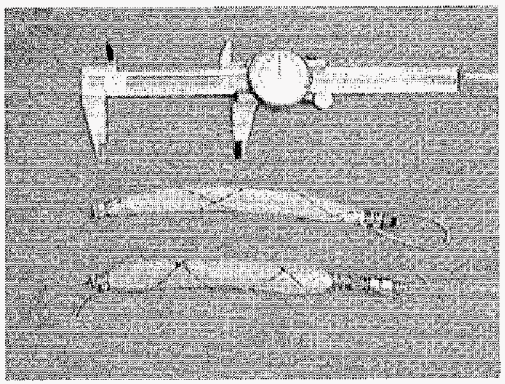
- The beginning of the field of EAP can be traced back to an 1880 experiment by Roentgen using a rubber-band that was charged and discharged with fixed end and a mass attached to the free end.
- Shortly afterward, Sacerdote [1899] formulated the strain response to electric field activation.
- These milestones were followed by Eguchi's 1925 discovery of electret materials*.
  - Obtained when carnauba wax, rosin and beeswax are solidified by cooling while subjected to DC bias field.
- Another important milestone is the 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 in last five years.

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

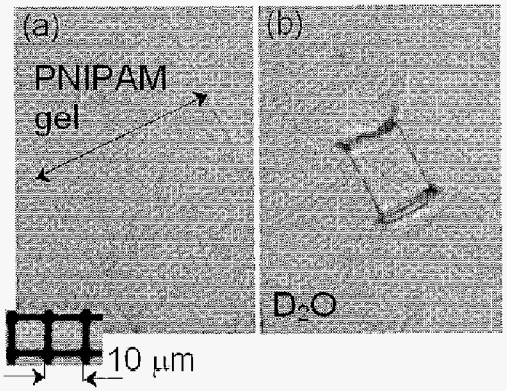
Non-Electrically Activatable Polymers

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

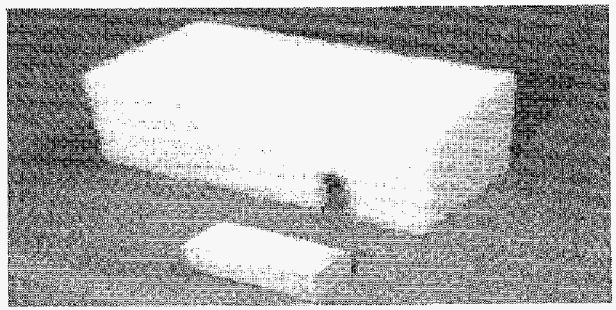
Non-Electrically activated Polymers



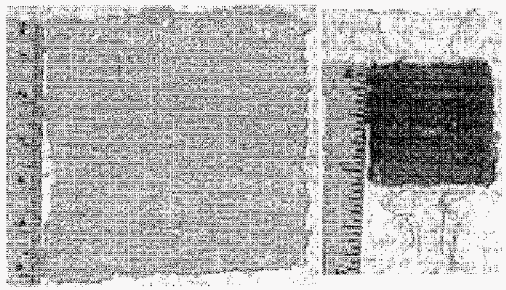
McKibben Artificial Muscles
Air Pressure activation (Hannaford, B.U. Washington)



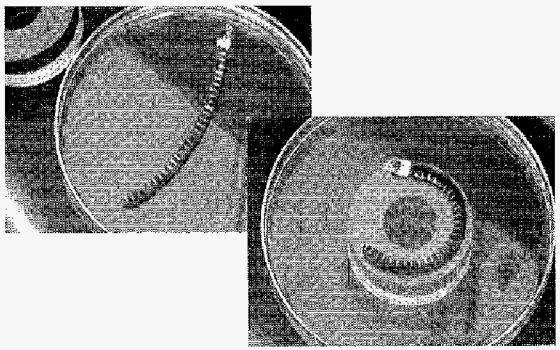
Laser Illuminated Polymer
Light activation (H. Misawa Japan)



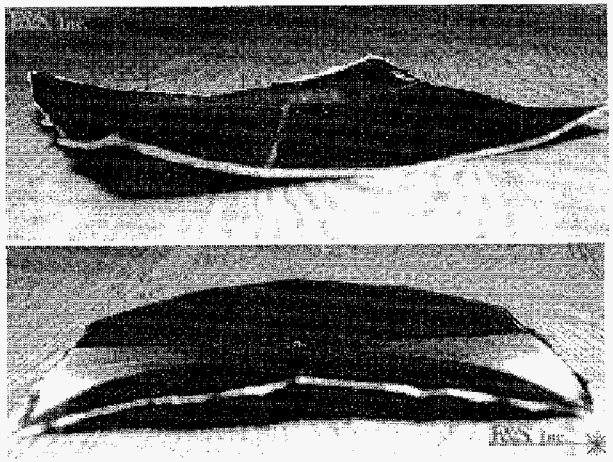
Shape Memory Polymers
Heat/pressure activation (W. Sokolowski, JPL)



Ionic Gel Polymers
Chemical transduction (P. Calvert, UA)



Ferrogel
Magnetic Activation (M. Zrinyi, Hungary)



Smart Structures
Polymers with Stable shapes (S. Poland, Luna Innovations, VA)

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COMPARISON BETWEEN EAP AND WIDELY USED TRANSDUCING ACTUATORS

Property	EAP	EAC	SMA
Actuation strain	>10%	0.1 - 0.3 %	<8% short fatigue life
Force (MPa)	0.1 – 3	30-40	about 700
Reaction speed	μsec to sec	μsec to sec	sec to min
Density	1- 2.5 g/cc	6-8 g/cc	5 - 6 g/cc
Drive voltage	2-7V/ 10-100V/μm	50 - 800 V	NA
Consumed Power*	m-watts	watts	watts
Fracture toughness	resilient, elastic	fragile	elastic

* Note: Power values are compared for documented devices driven by such actuators.

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COMPARISON BETWEEN EAP AND WIDELY USED TRANSDUCING ACTUATORS

Property	Electro-static silicone elastomer [Kornbluh]	Polymer Electrostrictor [Zhang]	SMA	Single Crystal Electrostrictor [Shrout]	Single Crystal Magnetostrictor [Clark]
Actuation strain	32 %	4 %	8 %	1.7 %	2 %
Blocking Force/Area *	0.2 MPa	0.8 MPa	700 MPa	65 MPa	100 MPa
Reaction speed	μsec	μsec	sec to min	μsec	μsec
Density	1.5 g/cc	3 g/cc	6 g/cc	7.5 g/cc	9.2 g/cc
Drive field	144 V/μm	150 V/μm	--	12 V/μm	2500 Oe
Fracture toughness	large	large	large	low	large

*Note: Values were calculated assuming the elastic properties were independent of applied field and are therefore approximate.

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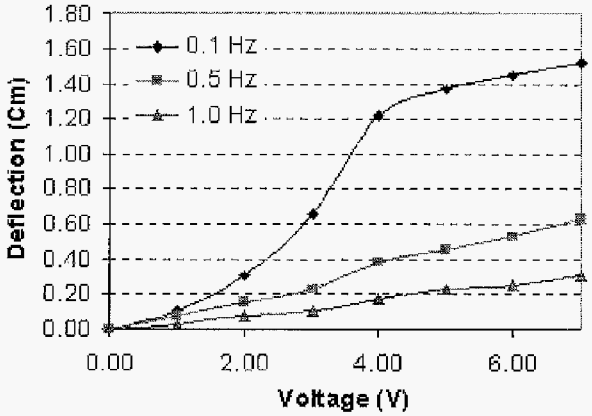
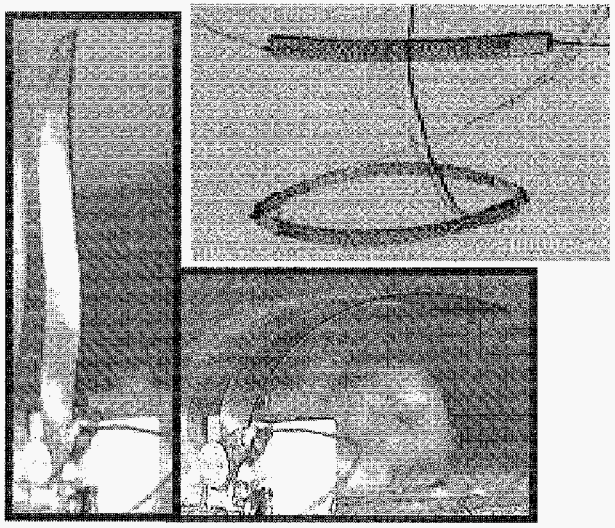
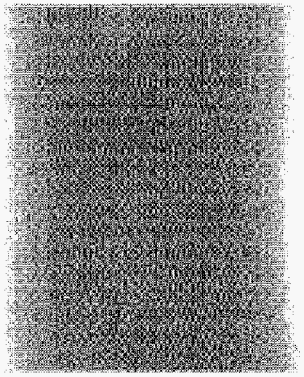
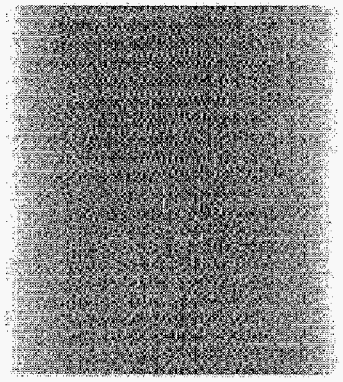
Bending and Longitudinal EAP Actuators





Ion-exchange Polymer Metal Composite (IPMC) can bend by over 90° under 1-4V.





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

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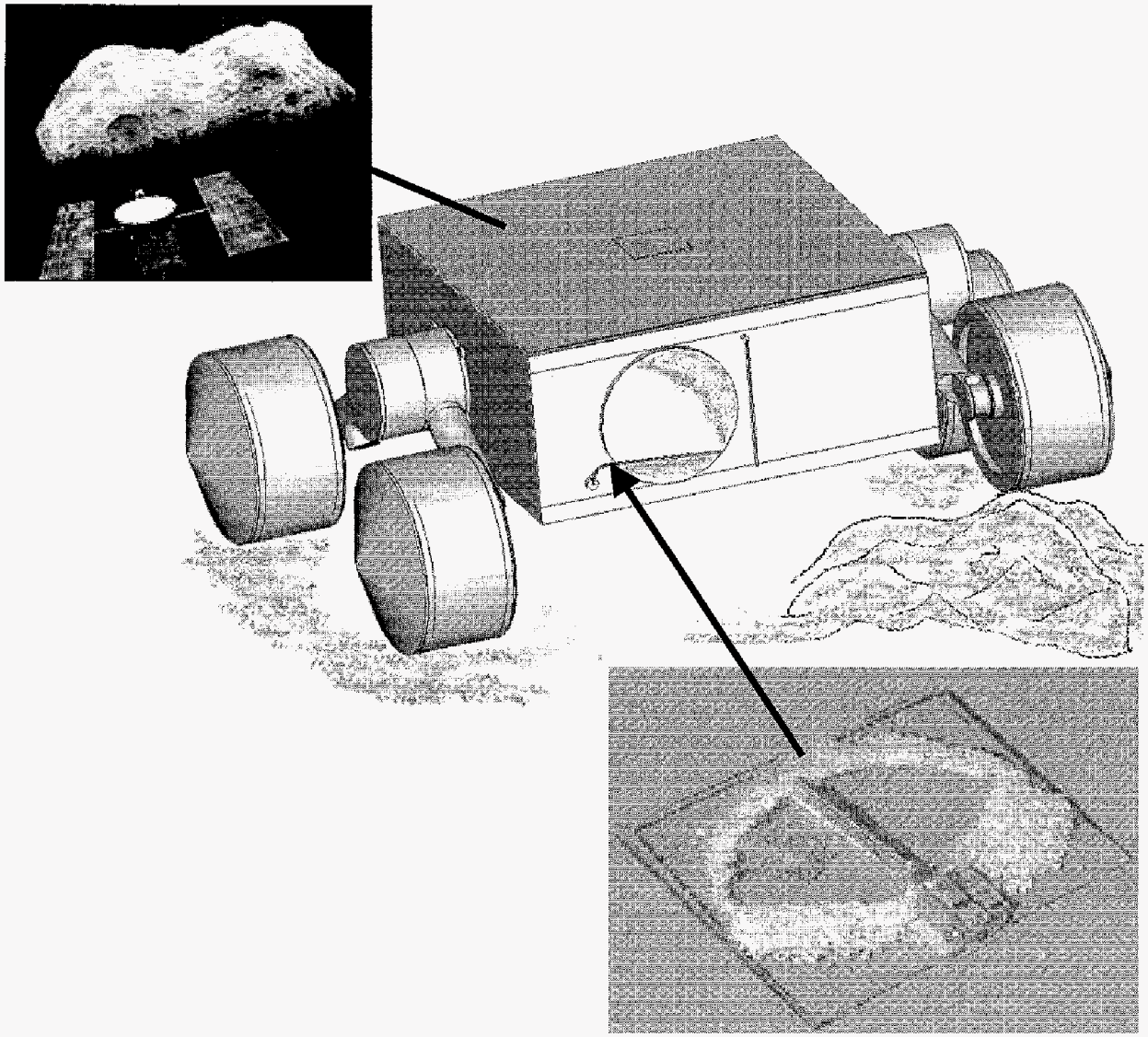
MUSES-CN Nanorover EAP Dust Wiper



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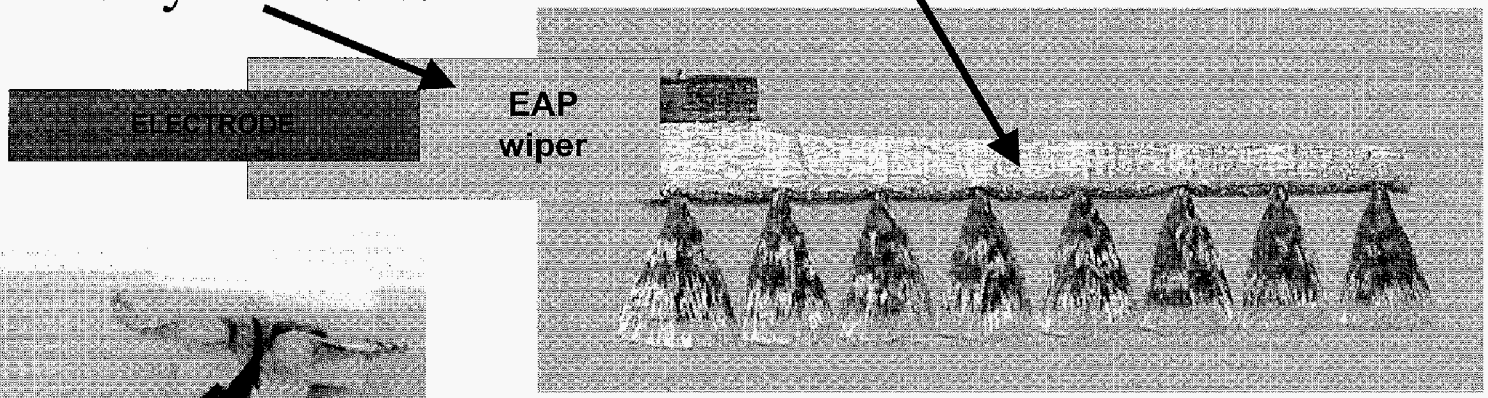
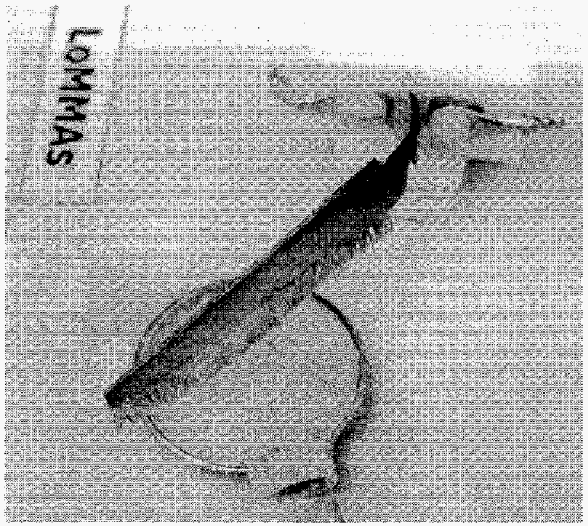
Surface wiper activated by EAP

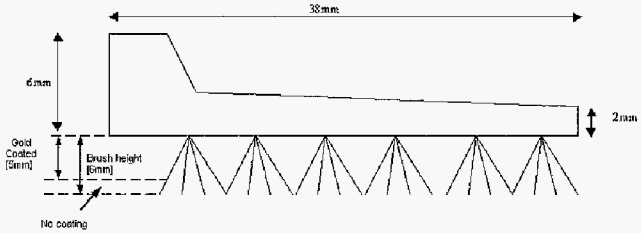
Actuated by 1-3 volts

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

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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
Operate at low temperatures	IPMC was demonstrated to respond at -100°C
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, and use cations such as Li^+ rather than Na^+.
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
Residual deformation particularly after intermittent activation	It occurs mostly after DC or pulse 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	Requires electrolyte with enriched cation content of the same species as in the IPMC

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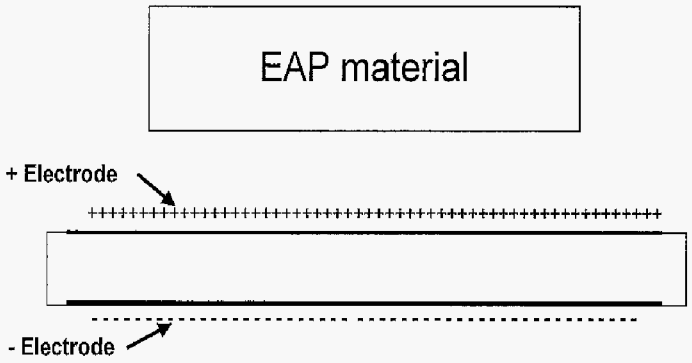
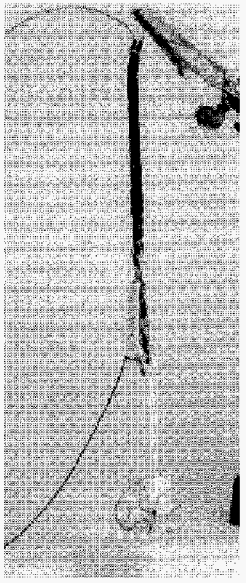
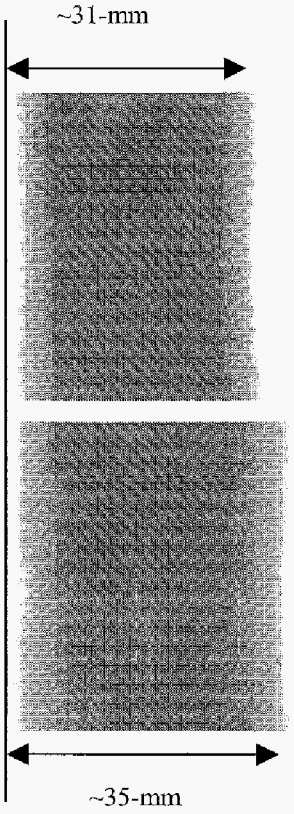
LONGITUDINAL EAP ACTUATOR

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







EAP film subjected to 25 V/μm induced over12% extension

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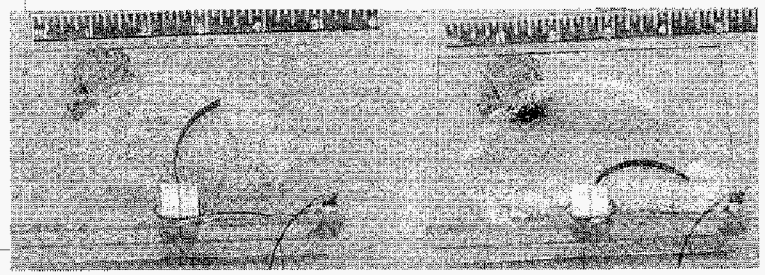
Electroactive Polymer (EAP) Actuators

Planetary application considerations at JPL

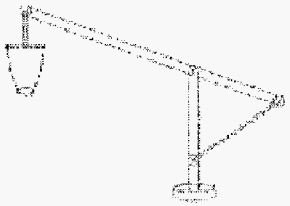
Dust wiper

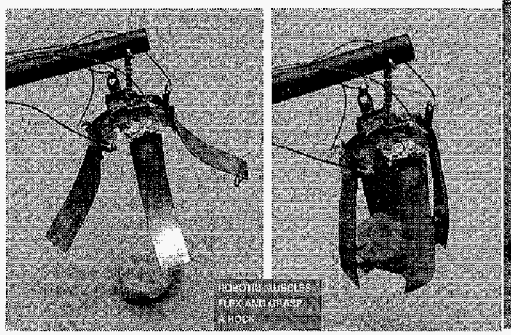
A bending EAP is used to develop a dust wiper

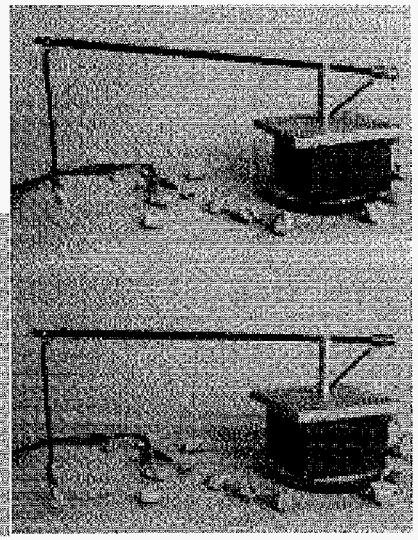


Miniature robotic arm

- A stretching EAP is used to lower a robotic arm, while bending EAP fingers operate as a gripper.
- Such technology can enable miniature sample handling robotics.







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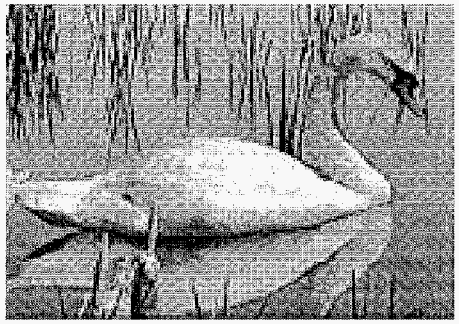
BIOLOGICALLY INSPIRED ROBOTICS

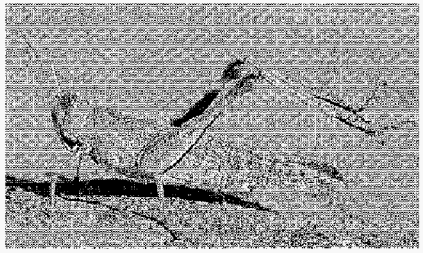
IN-SITU MULTI-TASKING MISSIONS USING SCALABLE AUTONOMOUS ROBOTS FOR COLONIZED PLANETARY EXPLORATION

Multiple locomotion capabilities

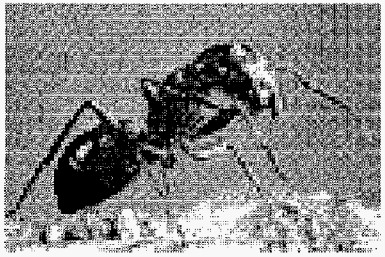
Flying, walking, swimming & diving



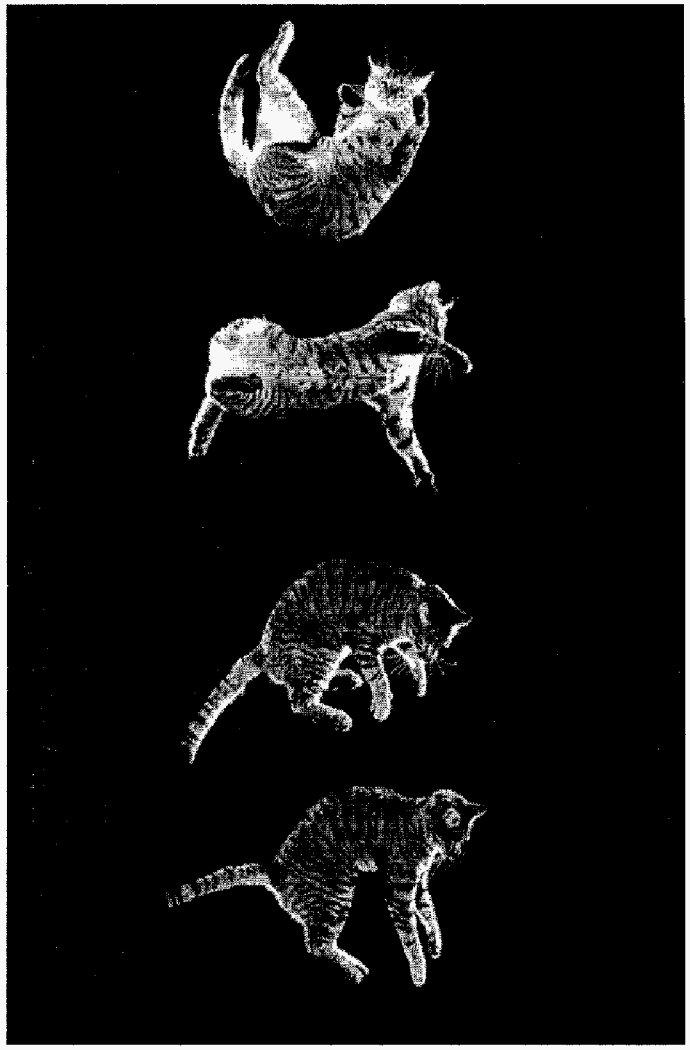
Hopping, flying, crawling & digging



Coordinated robotics



Models for EAP Actuated Flexible Robots



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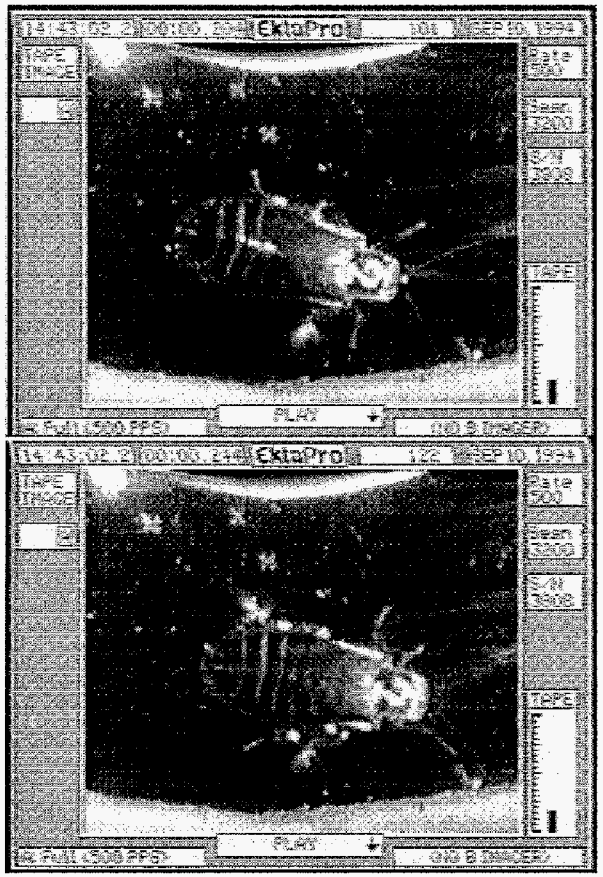
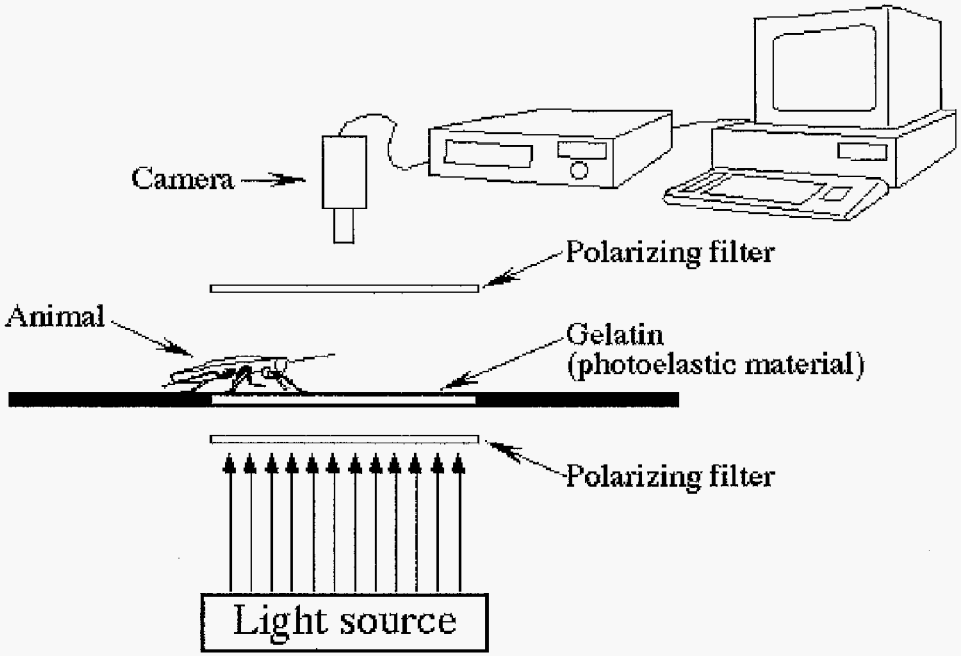
Insect walking process*

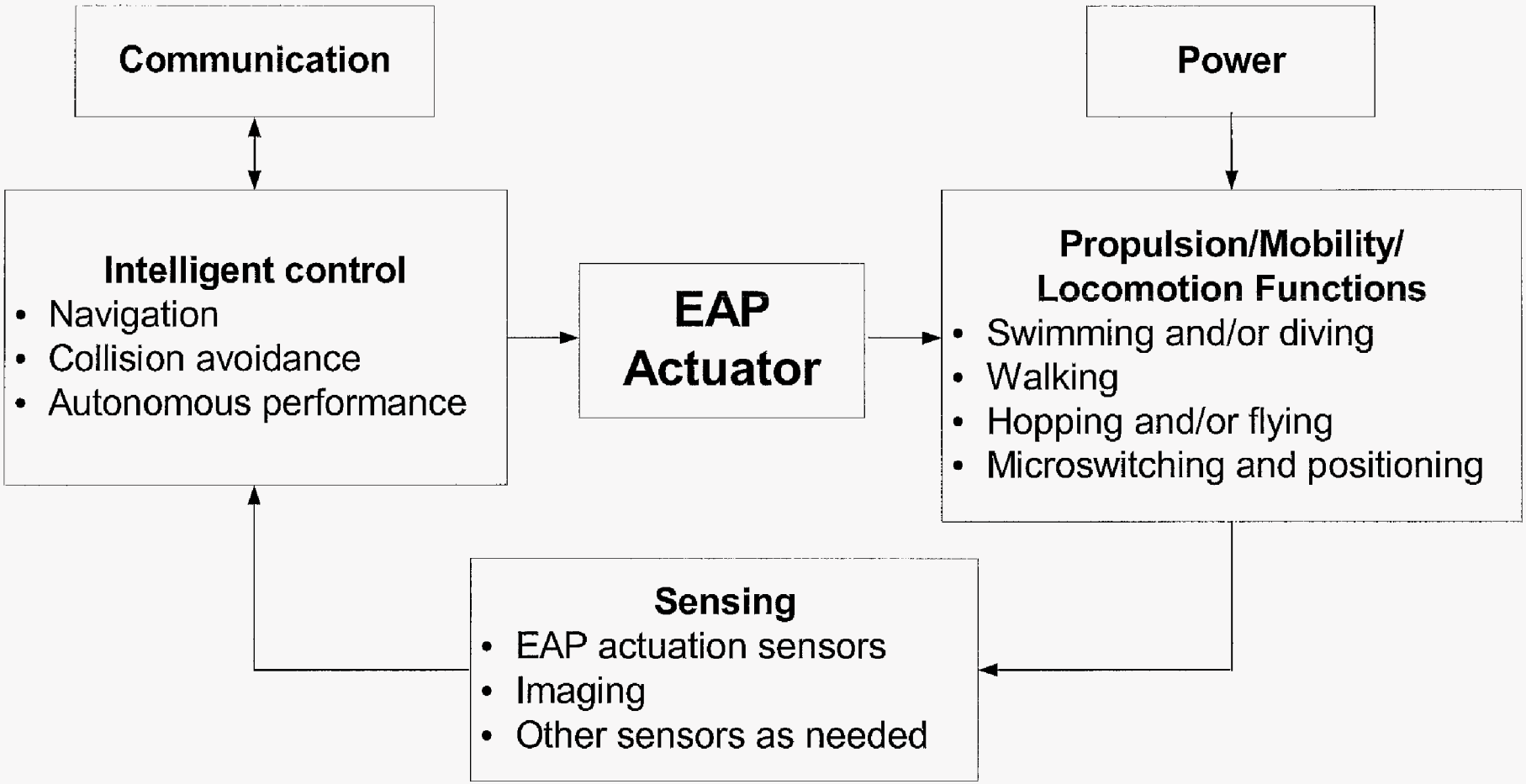


Photoelastic force platform is used at Berkeley to study insect walking mechanism.



* Robert Full, Berkeley U.
Ref: http://rjf2.biol.berkeley.edu/Full_Lab/FL_Publications/PB_Posters/94ASZ_Turning/94ASZ_Turning.html

ELEMENTS OF AN EAP ACTUATED ROBOTS



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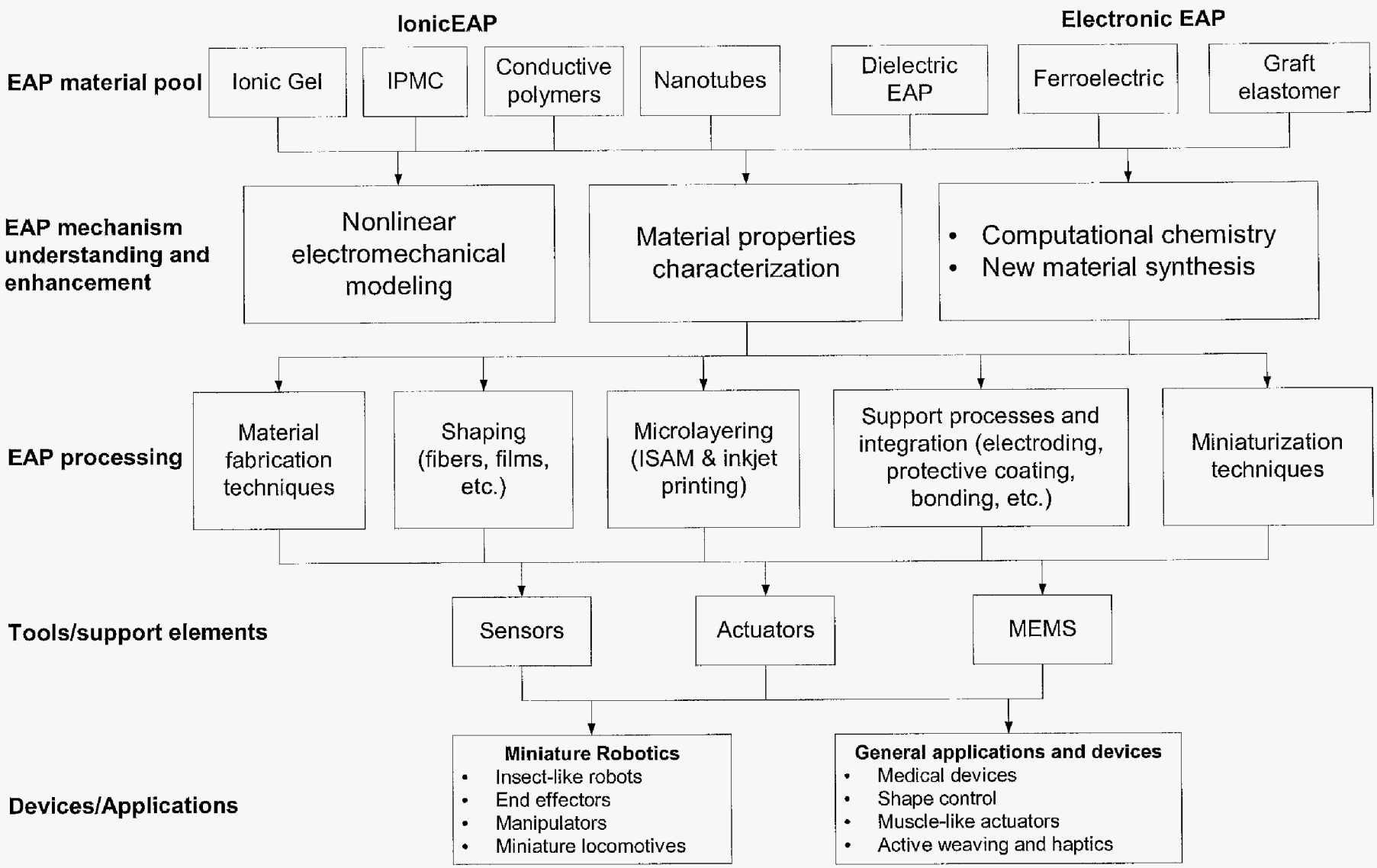
EAP infrastructure



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Electroactive Polymers (EAP)

IONIC EAP

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

ELECTRONIC EAP

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

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Current EAP
Advantages and disadvantages

EAP type	Advantages	Disadvantages
Electronic EAP	· Can operate in room conditions for a long time · Rapid response (μm levels) · Can hold strain under DC activation · Induces relatively large actuation forces	· Requires high voltages (~150 MV/m) · Requires compromise between strain and stress · Glass transition temperature is inadequate for low temperature actuation tasks
Ionic EAP	· Large bending displacements · Provides mostly bending actuation (longitudinal mechanisms can be constructed) · Requires low voltage	· Except for CPs, ionic EAPs do not hold strain under DC voltage · Slow response (fraction of a second) · Bending EAPs induce a relatively low actuation force · Except for CPs, it is difficult to produce a consistent material (particularly IPMC) · In aqueous systems the material sustains hydrolysis at >1.23-V

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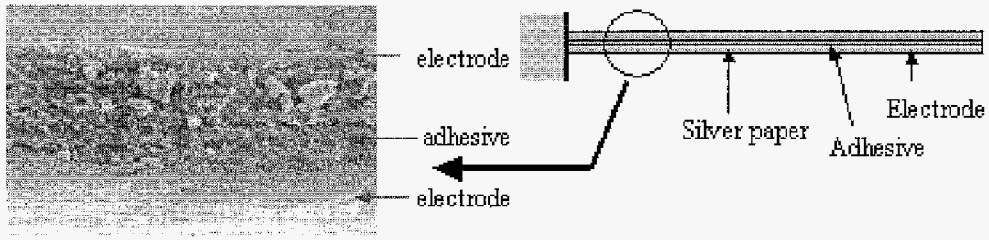
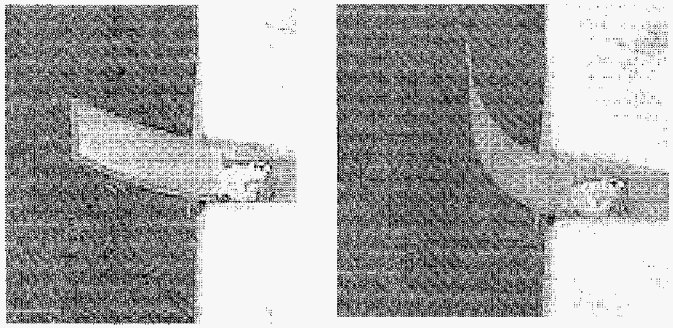
DRY EAP

ELECTRIC FIELD OR COULOMB FORCES DRIVEN ACTUATORS



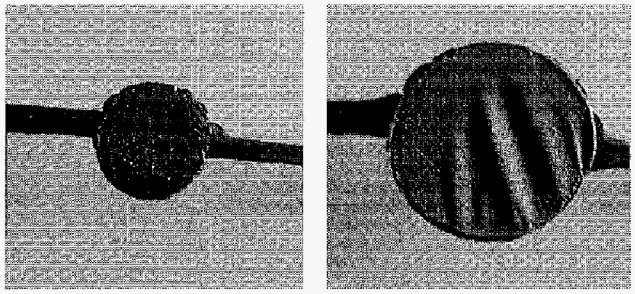
Paper as electrostrictive polymer

[Inha University, Korea]



Ferroelectric Bimorph

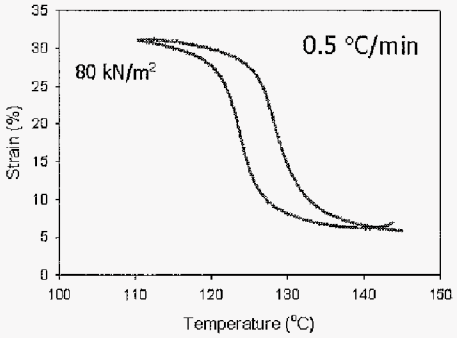
[Penn State U.]



Voltage Off **Voltage On**

Dielectric EAP

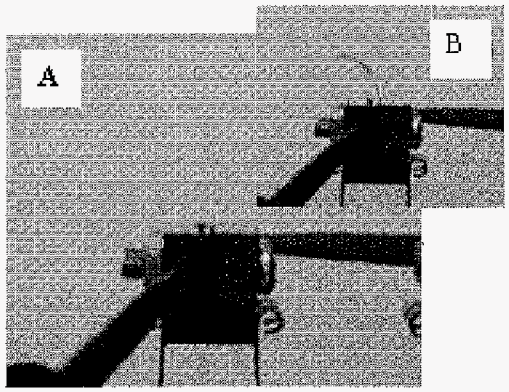
[SRI International]



Liquid Crystals

(Piezoelectric and thermo-mechanic)

[Naval Research Laboratory]



Graft Elastomer Bimorph

[NASA LaRC]

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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	Potentially capable of matching the force and energy density of biological muscles	Operate very slowly - it would require very thin layers and new type of electrodes to become practical	Poly(vinyl alcohol) gel with dimethyl sulfoxide, and polyacrylonitrile (PAN) with conductive fibers
Ion-Exchange 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.	• Require low voltage (1-10 V) • Provide significant bending • Potentially self-sensing	• Low frequency response (effectively below 1-Hz) • Extremely sensitive to dehydration and developed coating is ineffective. • DC permanent deform it • Hydrolysis above 1.23V • Displacement drift	Base polymer: • Nafion® (perfluorosulfonate made by DuPont) • Flemion® (perfluorocaboxylate, made by Asahi Glass, Japan). **Cations**: tetra-n-butylammonium, Li+, and Na+ **Metal**: Pt and Gold
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.	• Require relatively low voltage • Induce relatively large force • Extensive body of knowledge • Biologically compatible	• Need surface protection to operate in dry environment • Suffer fatigue after repeated activation of several Kcycles. • Slow response (<40-Hz)	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	• Potentially provide superior work/ cycle & mechanical stresses • Carbon offers high thermal stability at high temperatures <1000 °C	• Expensive • Difficult to mass produce	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	• Viscosity control for virtual valves • Enable haptic mechanisms with high spatial resolution	• Requires high voltage	Polymer particles in fluorosilicone base oil

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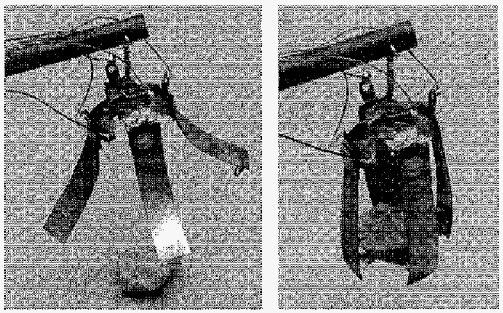
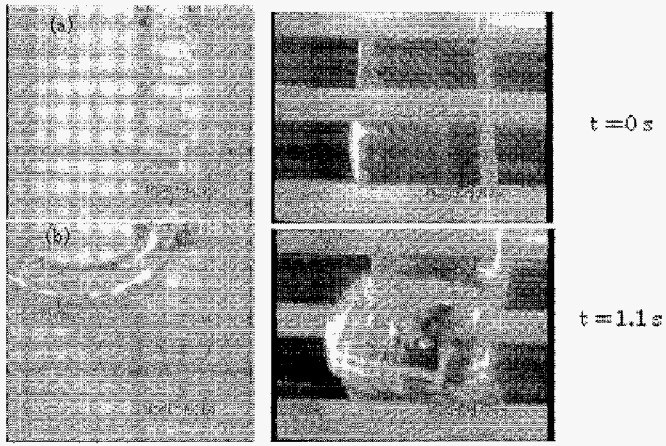
LIQUID OR WET EAP

Ionically and/or Electrolytically Activated



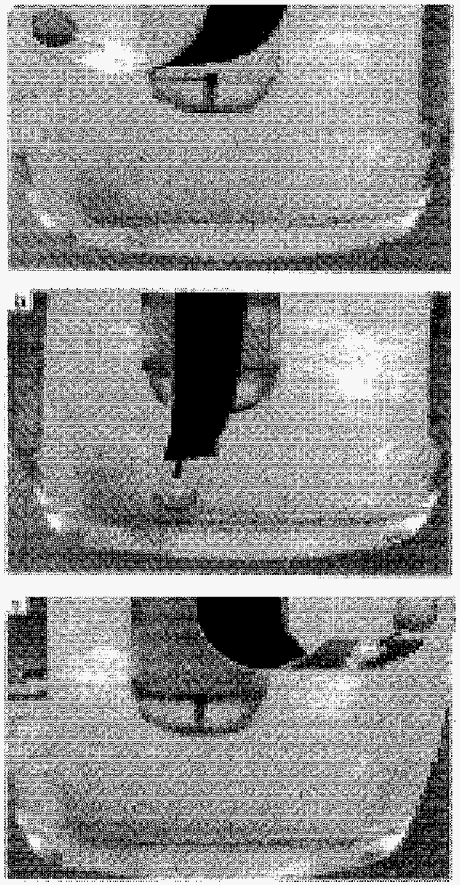
IPMC

[JPL using ONRI, Japan & UNM materials]



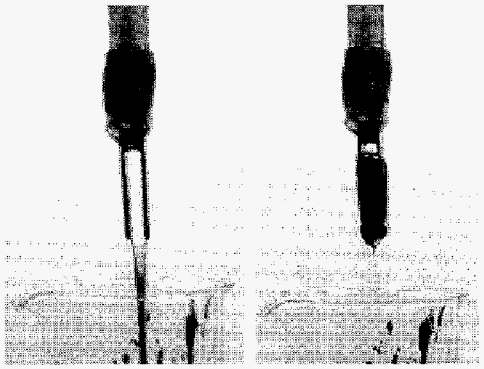
Ionic Gel

[Shinshu University, Japan]



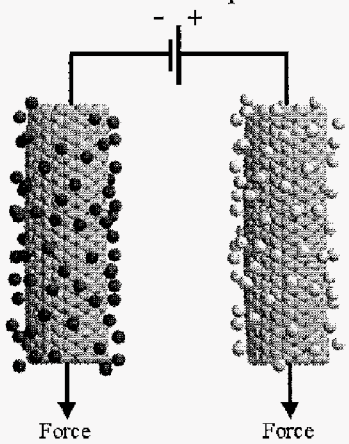
Conductive Polymer

[San Sebastian U., Spain, and JPL]



ElectroRheological Fluids (ERF)

[ER Fluids Developments Ltd]



Carbon-Nanotubes

[Honeywell, et al]

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Electronic EAP

Actuator type	Principle	Advantages	Disadvantages	Reported Types
Ferroelectric Polymers	Polymers that exhibit noncentro-symmetric sustain 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	• Induce relatively large strain (~5%). • Offer high mechanical energy density resulting from the relatively high elastic modulus • Permit AC switching with little generated heat • Rapid response (μm levels)	• Require high voltage (~150 MV/m) • Applying radiation is expensive • Difficult to mass produce • Making thin multilayers is still a challenge.	Electron radiated P(VDF-TrFE)
Dielectric EAP or ESSP	Coulomb forces between the electrodes squeezes 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 200-300%.	• Large displacements reaching levels of 200-300% • Rapid response (μm levels) · Inexpensive to produce	• Require high voltage (~150 MV/m) • Obtaining large displacements compromises the actuation force • Require pre-strain	• Silicone • Polyurethane
Electrostrictive Graft Elastomers	Electric field causes molecular alignment of the pendant group made of graft crystalline elastomers that are attached to the backbone.	• Strain levels of 5% • Relatively large force • Cheaper to produce • Rapid response (μm levels)	• Require high voltage (~150 MV/m)	Copolymer – poly(vinylidenr fluoride-trifluoroethylene)
Liquid Crystal Elastomers	• Contract when heated • Exhibit spontaneous Ferroelectricity	• Induce large stress and strain (~ 200kPa and 45%, respectively) • Rapid response (μm levels)	• Slow response • Hysteresis	• Polyacrylate • polysiloxane

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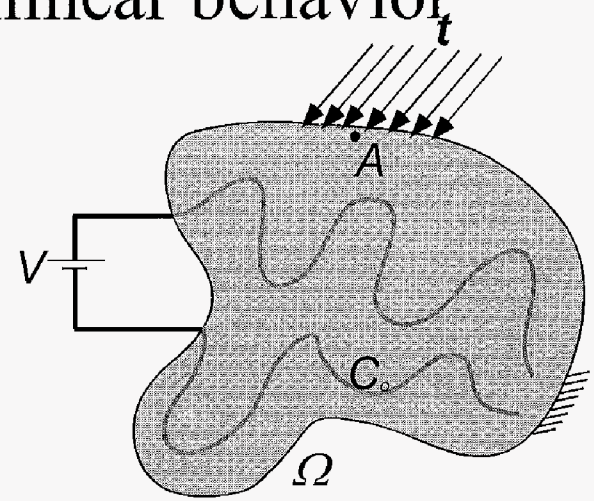
Modeling EAP including their nonlinear behavior

Objective: Maximise the stretch in the direction e amongst all possible configurations of conductors C and domains shape Ω .

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 (non-linear) deformation theory.

Mathematically:

$$\max_{\substack{C^{\pm} \subset C_0 \\ vol(\Omega)=1}} \int_{\Omega} |(\nabla y)e|^2 dx$$

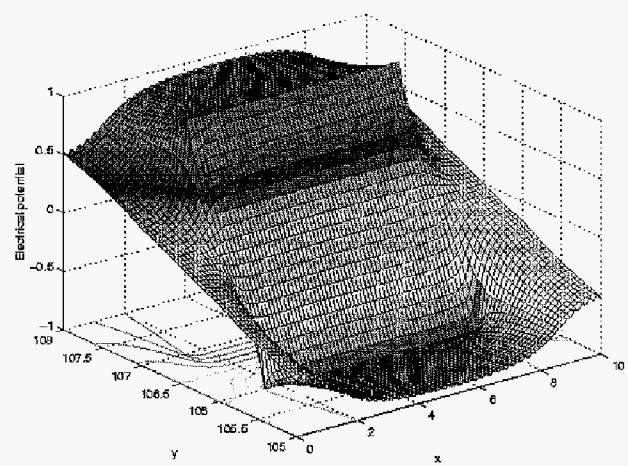


Where:

y deformation
e stretch direction
C conductor configurations
Ω domain shapes
V electric potential
W strain energy density
t applied stress

Numerical implementation using ABAQUS

1. Solve coupled electro-mechanical problem
   a. Solve electrostatic problem
   b. Calculate forces
   c. Solve finite elasticity problem
   d. Deform electrodes and iterate
2. Calculate configurational forces on conductors
3. Change conductor configuration
4. Iterate



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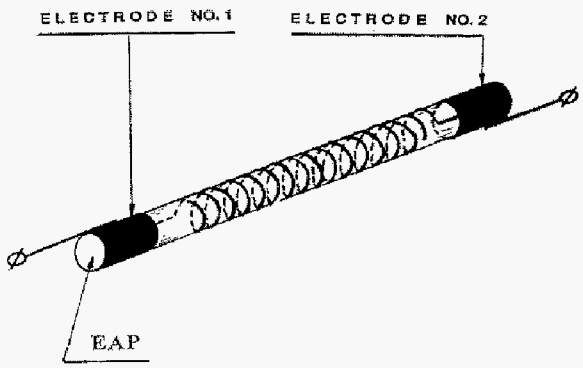
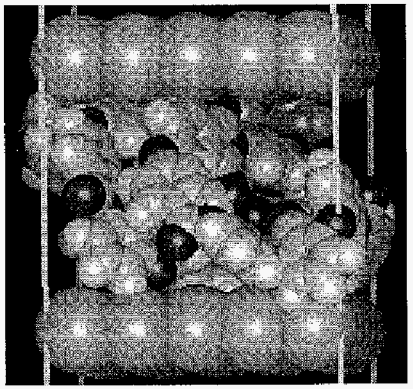
New EAP processes

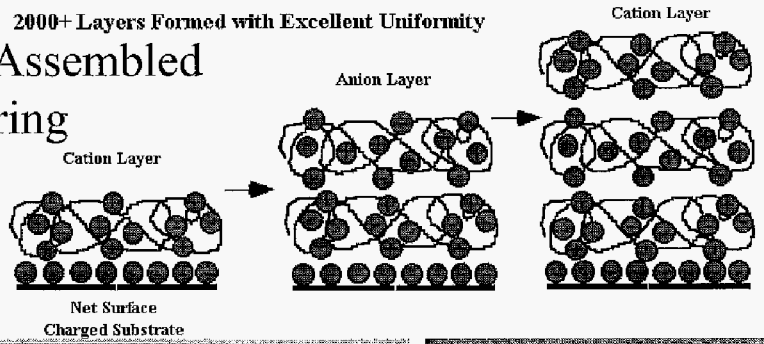


New material design tools: Computational chemistry

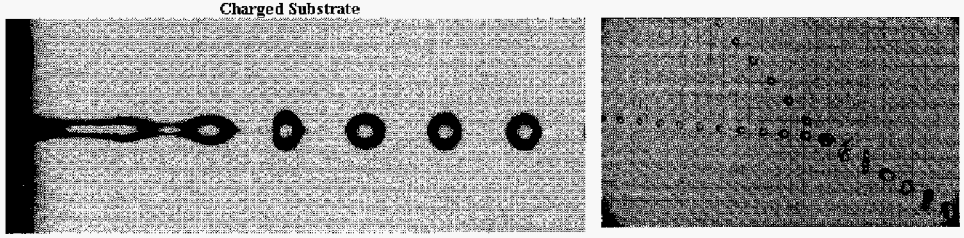


New processing, shaping and electroding methods
Forming actuator bundles

Ionic Self-Assembled mono-layering



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



50-μm drops jet

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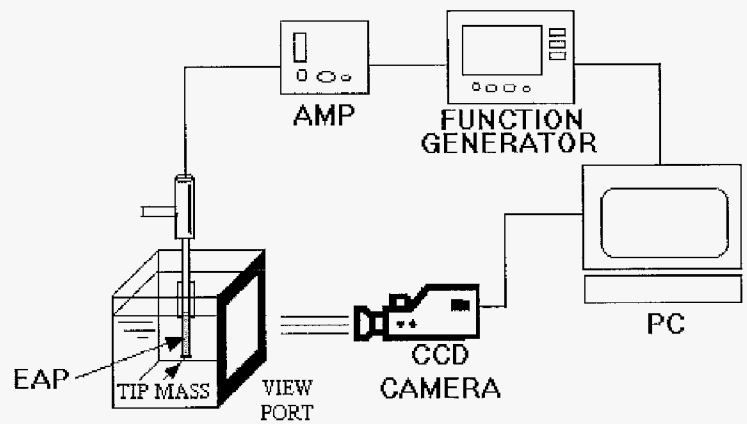
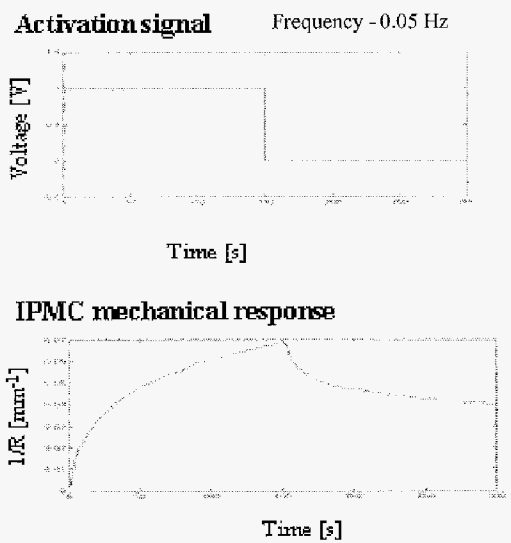
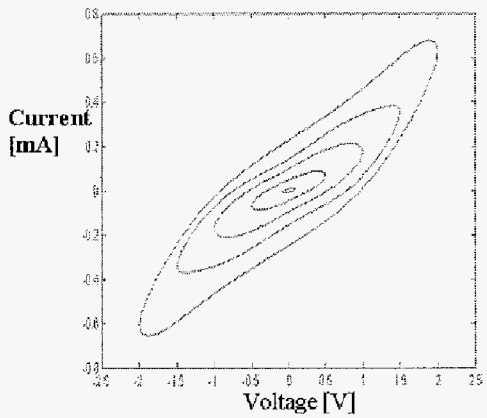
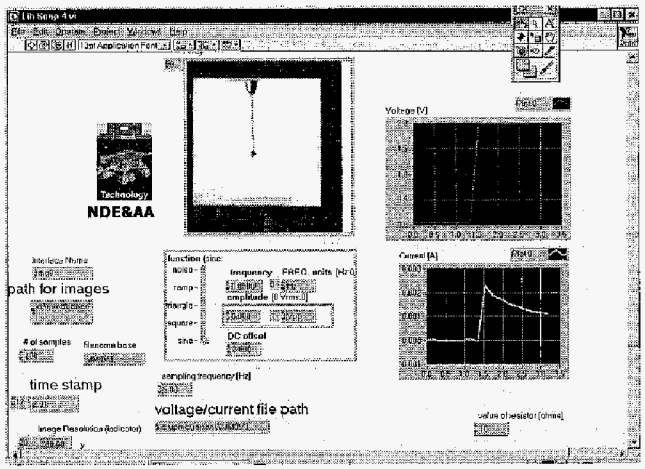
EAP Material Characterization

- 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









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Actuators Specifications*

Parameter	Scale-Invariant Version	Comments
Energy and Power		
Energy output	Specific energy	Over full cycle
Power output	Specific power	Average or instantaneous
Energy conversion efficiency	Same	Energy out over a full cycle / energy in over a full cycle (excluding recovered energy)
Response time	Same (response time is not generally scale invariant)	For one direction or full cycle
State Variables		
Displacement	Strain	Instantaneous or maximum over a cycle
Force	Stress, pressure	Instantaneous or maximum during a cycle
Velocity	Strain rate	Instantaneous or maximum
Impedance and Controllability		
Stiffness	Elastic modulus	Usually nonlinear (not a constant)
Damping	Specific damping, loss factor, loss tangent	Usually nonlinear (not a constant)
Accuracy (displacement or force) (%)	Percentage of strain or stress	Usually percentage of maximums
Repeatability (%)	Same	Usually percentage of maximums
Linearity or sensitivity (%)	Same	Deviation from linear input-output relationship
Operational Characteristics		
Environmental tolerance	Same	Ranges of Temp., humidity, etc., or effect of variations on temperature, humidity, etc., on the above parameters
Durability, reliability	Same	Number of cycles before degradation threshold or total failure, degradation per cycle or time
Input impedance (power supply requirements)	Specific impedance	Voltage and current requirements or pressure and flow, depending on power mode

*** Kornbluh and Perline, 2001**

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EAP Properties of Test Metric

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 & EAP), internal structure, uniformity and anisotropy as well as identify defects.	These are features that will require establishing 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

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Potential EAP applications

- EAPs offers unique characteristics to produce highly maneuverable, noiseless, agile biologically-inspired mechanisms.
  - Potentially operate a locomotion mechanism of insect-like (flying, crawling, swimming, etc.) at sizes that range from microns to several centimeters.
- EAP can be used to provide actuators that require simple drive signals but their nonlinear behavior needs to be taken into account.
- The development and application of 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

- Robotics, Toys and Animatronics
  - Biologically-Inspired and Insect-Like Robots
  - Toys and Animatronics
  - Agriculture and Ecology
- Human-Machine Interfaces
  - Haptic Interfacing – "Feeling" Virtual or Remote Stiffness and Forces
  - Tactile Interfaces
  - Simulated Texture
  - Orientation Indicator – Smart Flight/Diving Suits
  - Tactile Display for Reading by Blind Persons
  - Artificial Nose
- Planetary Applications
  - International Space Station - MISSE
- Controlled Weaving
  - Garment and Clothing
  - Anti G-Suit
- 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
  - Jet Flow Control
- Noise Reduction
- MEMS
- EM Polymer Sensors &Transducers

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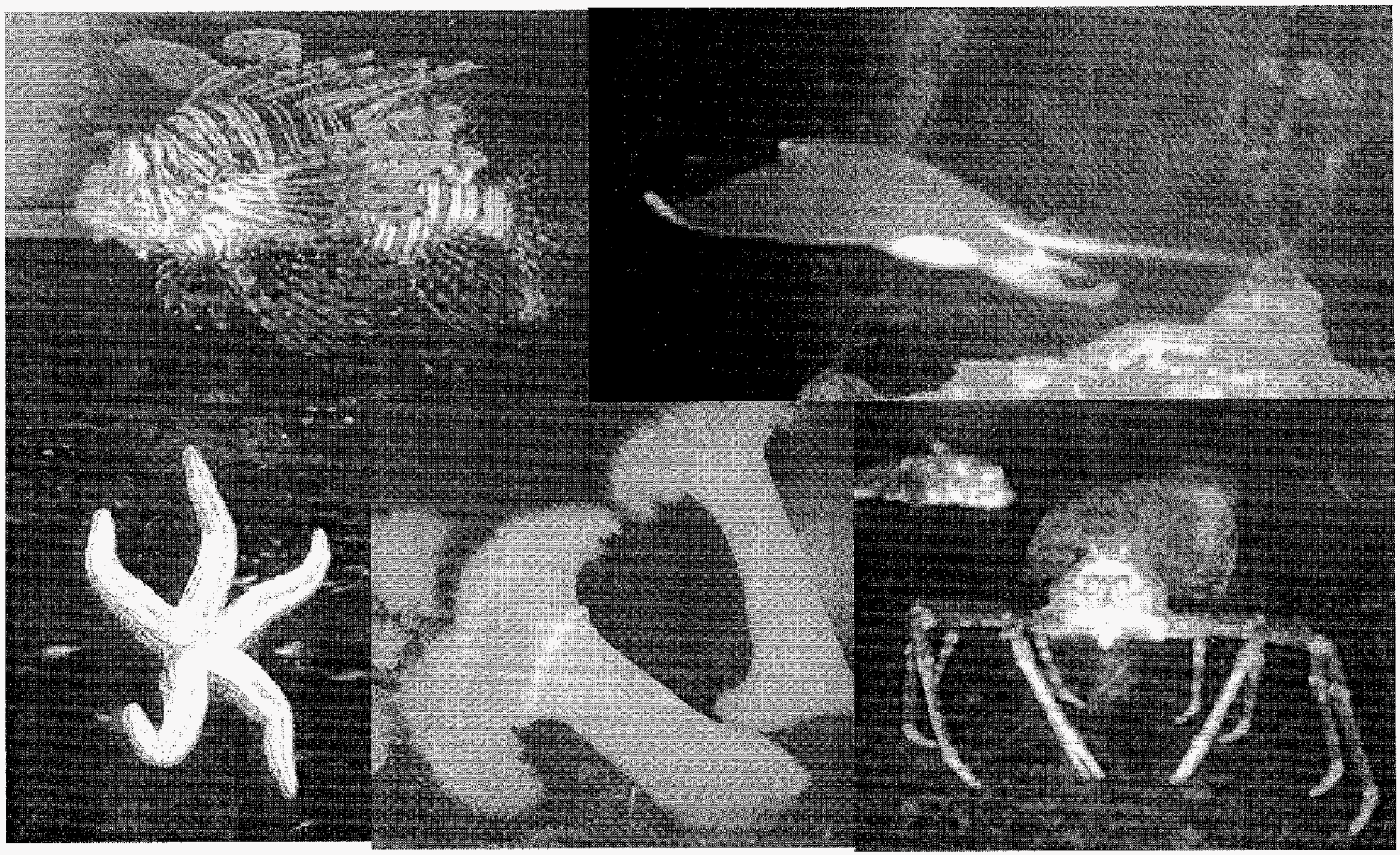
A challenge to EAP
Emulating sea creatures



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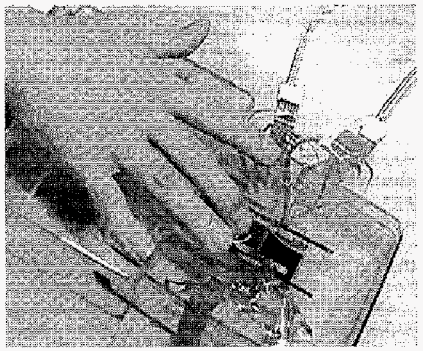
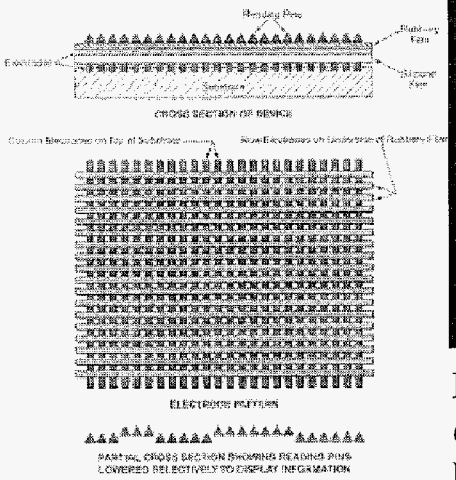
Human-Machine Interfaces

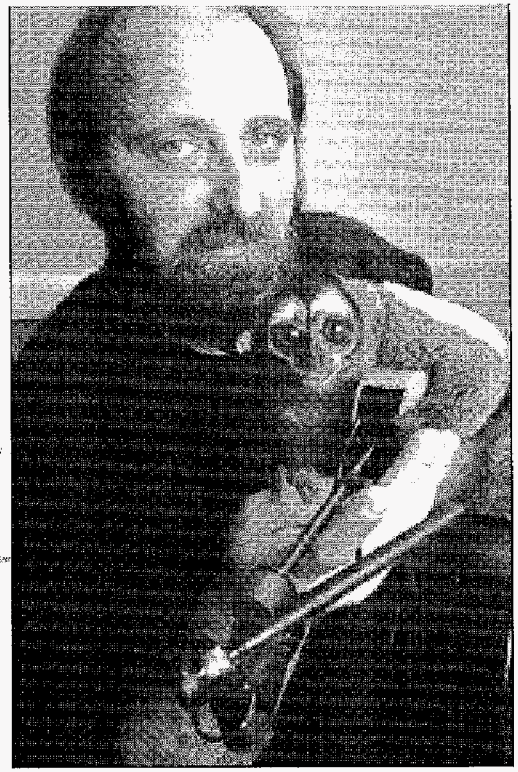
- Interfacing human and machine to complement or substitute our senses would enable important medical applications.
- Researchers at Duck U. connected electrodes to a brain of a money and were able to control a robotic arm. This breakthrough opens the possibility that the human brain would be able to 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



Reading display for blind persons



Miguel Nicolelis and his team used electrodes connected to a monkey's brain to control a robotic arm

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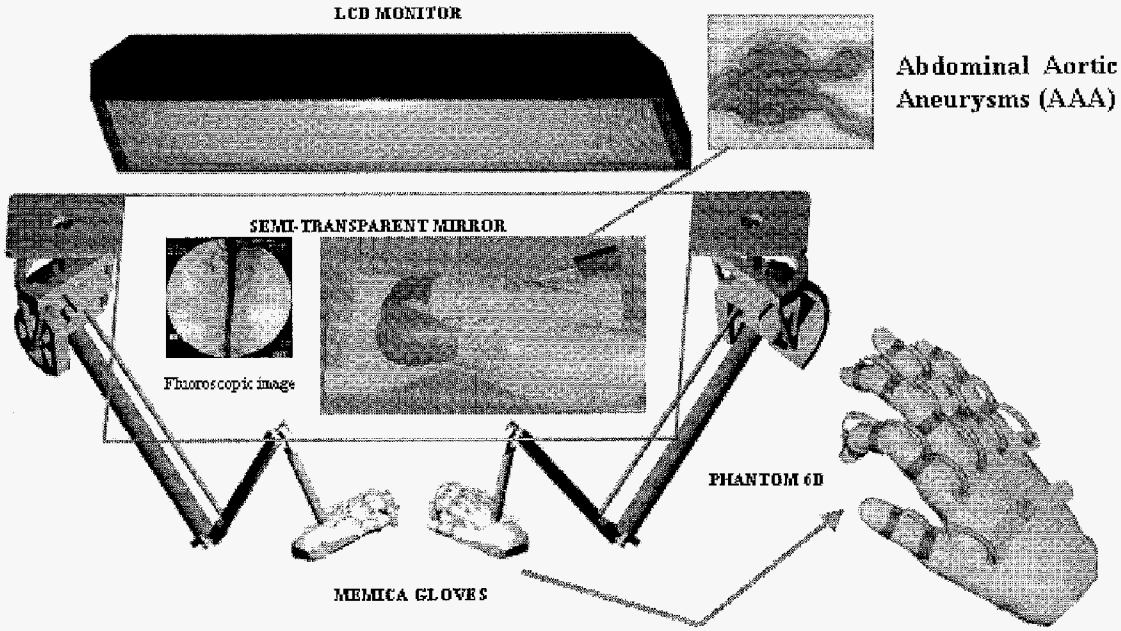
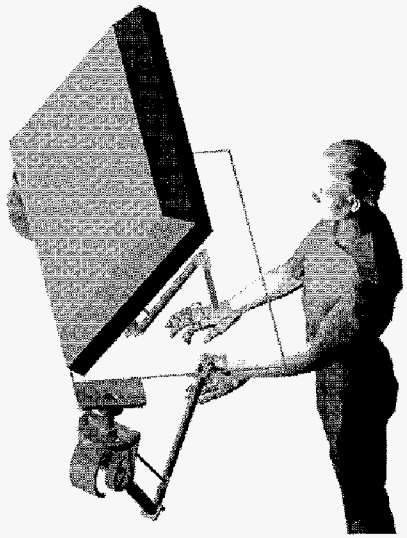
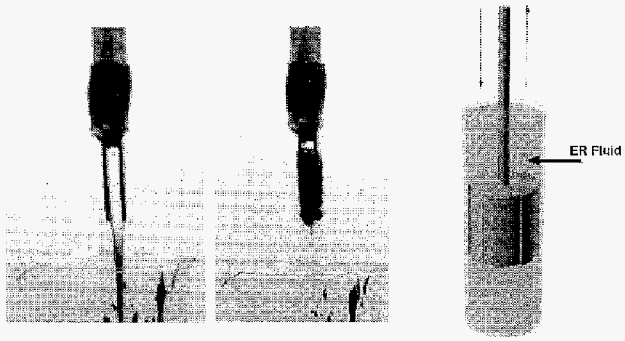
MEMICA (remote MEchanical MIrroring using Controlled stiffness and Actuators)

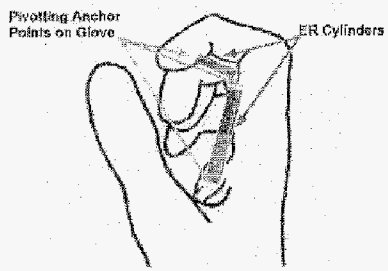


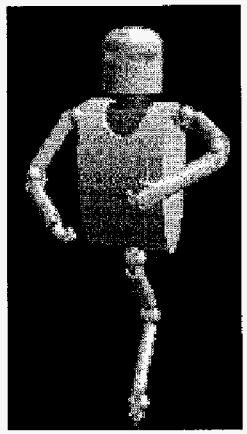
Abdominal Aortic Aneurysms (AAA)



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







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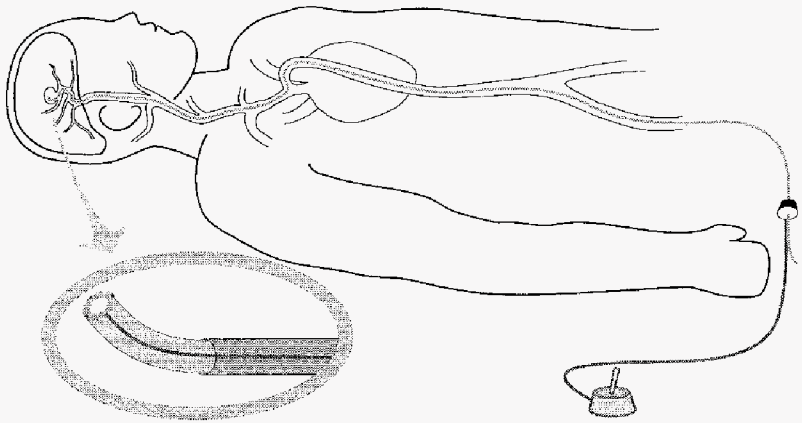
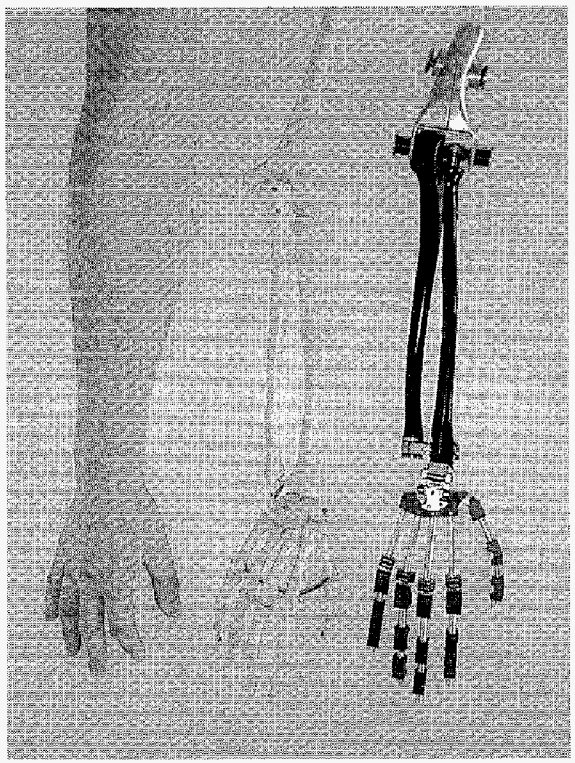
Medical Applications

- 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





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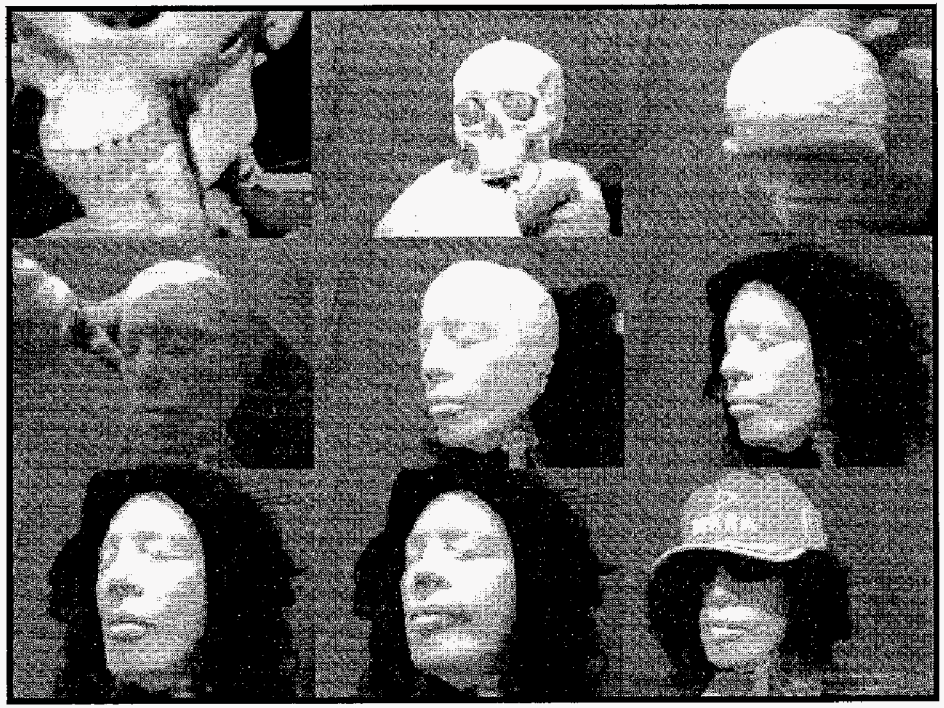
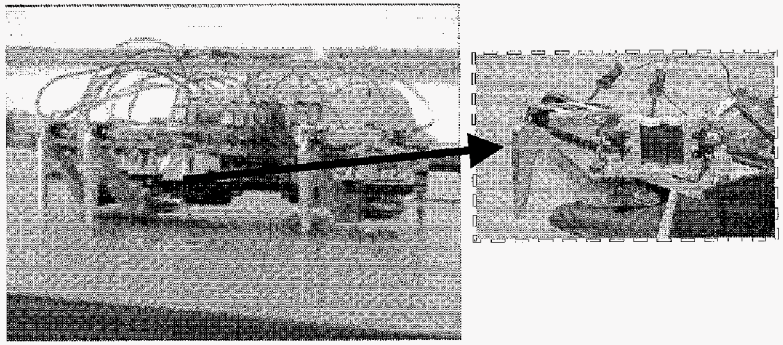
Robotics, Toys and Animatronics

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

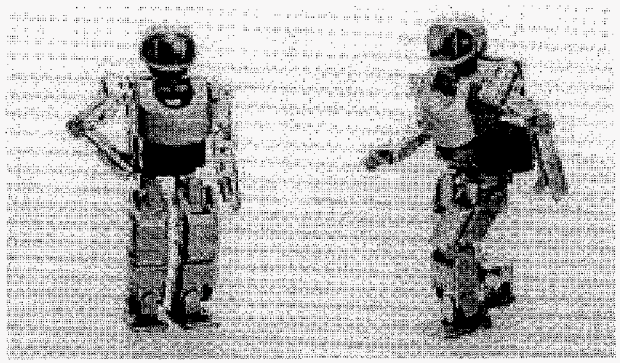


Android making facial expressions (U. of Pisa, Italy)



Hexapod robot powered by dielectric EAP (SRI International)

Desired capability:



Sony's SDR3

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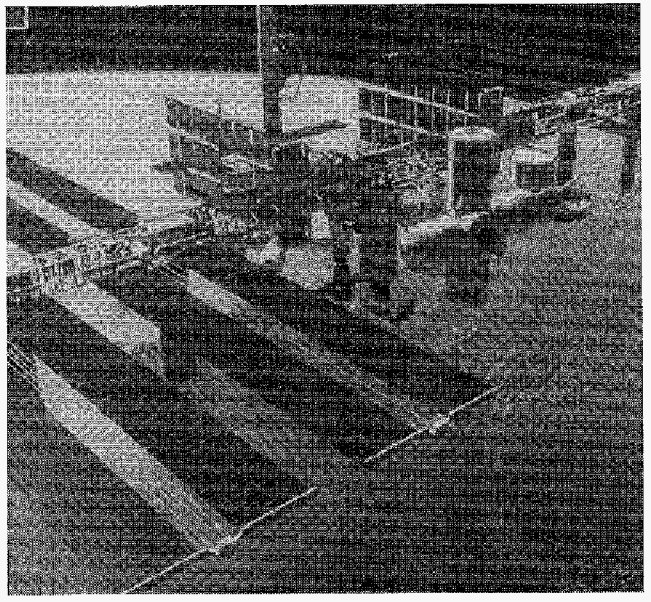
INTERNATIONAL SPACE STATION - MISSE EXPERIMENT

- The International Space Station (ISS) is offering unprecedented opportunities for long-term experiments in space.
- One of the first of such experiments is the Materials International Space Station Experiment (MISSE) sponsored by the AFRL/ML and the NASA SEE Program [Cooperative effort between the Air Force, NASA and industry].
- Material specimens will be placed in 4 separate Passive Experiment Carriers (PECs) previously used to contain the MIR Environmental Effects Payload experiments on MIR from March 1996 to September 1997.
- The MISSE PECs will be installed external to the ISS in late 2000 to early 2001, subject to approval by the NASA ISS program and flown for periods of 1 to 3 years.
- The experiment time frame will correspond to solar maximum conditions, providing as severe a test environment in low earth orbit as possible.
- EAP was offered an opportunity to fly on the autonomous experiment and a small area was allocated.



PI: Suzanne L. B. Woll, Ph.D. Non-metallic Materials Technology Boeing Phantom Works, (425) 965-0672 Renton

International technical forums for interaction and collaboration

- SPIE Smart Structures and Materials Symposium - EAP Actuators and Devices Conference - held for the first time on March 1-2, 1999 in Newport Beach, CA
- MRS Conference - Symposium FF: Electroactive Polymers - held for the first time on Nov. 29 to Dec. 3, 1999 in Boston, MA
- In March 1999 - An EAP Actuators Worldwide webhub was formed with links to EAP R&D sites, general information and databases.
  http://ndeaa.jpl.nasa.gov/nasa-nde/lommas/eap/EAP-web.htm
- In June 1999, the first WW-EAP Newsletter issue was published electronically
  http//ndeaa.jpl.nasa.gov/nasa-nde/lommas/eap/WW-EAP-Newsletter.html
- In Nov. 1999 - An electronic communication platform (newsgroup) was formed. To register send eap-request@artemis.arc.nasa.gov "subscribe eap"

WW-EAP Homepages

Links for the Webhub: http://ndeaa.jpl.nasa.gov/nasa-nde/lommas/eap/EAP-web.htm

- Biological Muscles: Dr. Richard L. Lieber article
  http://eis.jpl.nasa.gov/ndeaa/ndeaa-pub/SPIE-lieber-muscle-99.pdf

- EAP Recipes: EAP preparation processes
  http://ndeaa.jpl.nasa.gov/nasa-nde/lommas/eap/EAP-recipe.htm

- EAP in Action: Short videos showing various EAP materials and mechanisms being activated
  http://ndeaa.jpl.nasa.gov/nasa-nde/lommas/EAP-video/EAP-videos.html

- EAP Database: A table of EAP was provided with a disclaimer
  http://ndeaa.jpl.nasa.gov/nasa-nde/lommas/eap/actuators-comp.pdf

- EAP References: A collection of references on EAP
  http://ndeaa.jpl.nasa.gov/nasa-nde/lommas/eap/EAP-references.htm

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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Manuscripts Due 5 February 2001

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Proceedings of SPIE Vol. 4329

Electro-Active Polymer Actuators and Devices

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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. Kornbluh,** 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,** Risö 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)

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

Book on EAP, SPIE Press, 2001

Y. Bar-Cohen (Ed.)

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 – Q. Zhang, Penn State U. and J. Scheinbeim, Rutgers U.
- *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
- Chapter 12.0 - Electro-mechanical models for optimal design and effective behavior – K. Bhattacharya, J. Li and X. Yu, Caltech
- Chapter 13.0 - Modeling IPMC for design of actuation mechanisms – S. Tadokoro, T. Takamori, Kobe U., and K. Oguro, ONRI, Japan

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Topic 5: Processing and Fabrication of EAP

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

Topic 6: Testing and Characterization

- Chapter 15.0 - Methods and Testing and Characterization –S. Sherrit, and Y. Bar-Cohen, JPL

Topic 7: EAP Actuators, Devices and Mechanisms

- Chapter 16.0 - Application of Dielectric EAP Actuators– R. Kornbluh and R. Pelrine, SRI International
- Chapter 17.0 - Biologically-inspired Robots –B. Kennedy, JPL, C. Melhuish, and A. Adamatzky, University of the West of England
- Chapter 18.0 - Applications of EAP to Entertainment Industry –D. Hanson, Disney Imagineering, and G. Pioggia, Pisa U., Italy
- Chapter 19.0 - Haptic Interfacing via ERF – D. Mavroidis, Rutgers U., Y. Bar-Cohen, JPL, and M. Bouzit, Rutgers U.
- Chapter 20.0 - Shape Control of Precision Gossamer Apertures– C. H.M. Jenkins, SDSMT

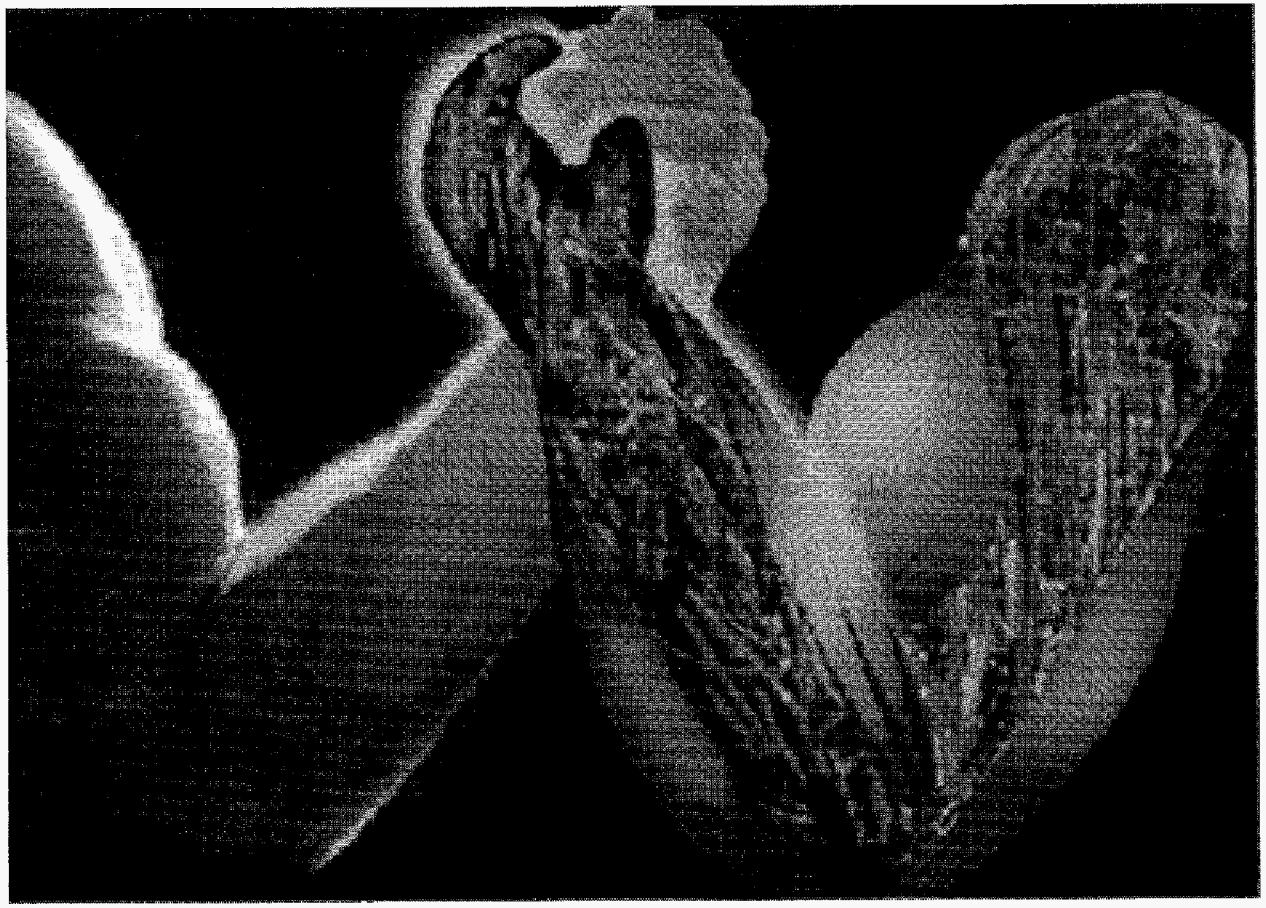
Topic 8: Lesson Learned, Applications and Outlook

- Chapter 21.0 - EAP Applications, Potentials and Challenges– Y. Bar-Cohen, JPL

SUMMARY

- Electroactive Polymers are emerging as effective displacement actuators.
- These materials offer the closest resemblance of biological muscle potentially enabling unique capabilities changing the paradigm about robots construction.
- Under the NASA's LoMMAs task, a series of EAP driven mechanisms were developed including dust wiper, gripper and robotic arm
- EAP are inducing a low actuation force limiting the applications that can use their current capability
- In recognition of this limitation a series of international forums were established including conferences [SPIE (March) and MRS (Dec.)], Webhub, Newsletter, and Newsgroup.
- A challenge was posed to the EAP community to have an arm wrestling between robot that is equipped with EAP actuators and human.

The grand challenge for EAP as
ARTIFICIAL MUSCLES



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