ELECTROACTIVE POLYMERS AS ARTIFICIAL MUSCLES – *REALITY AND CHALLENGES*

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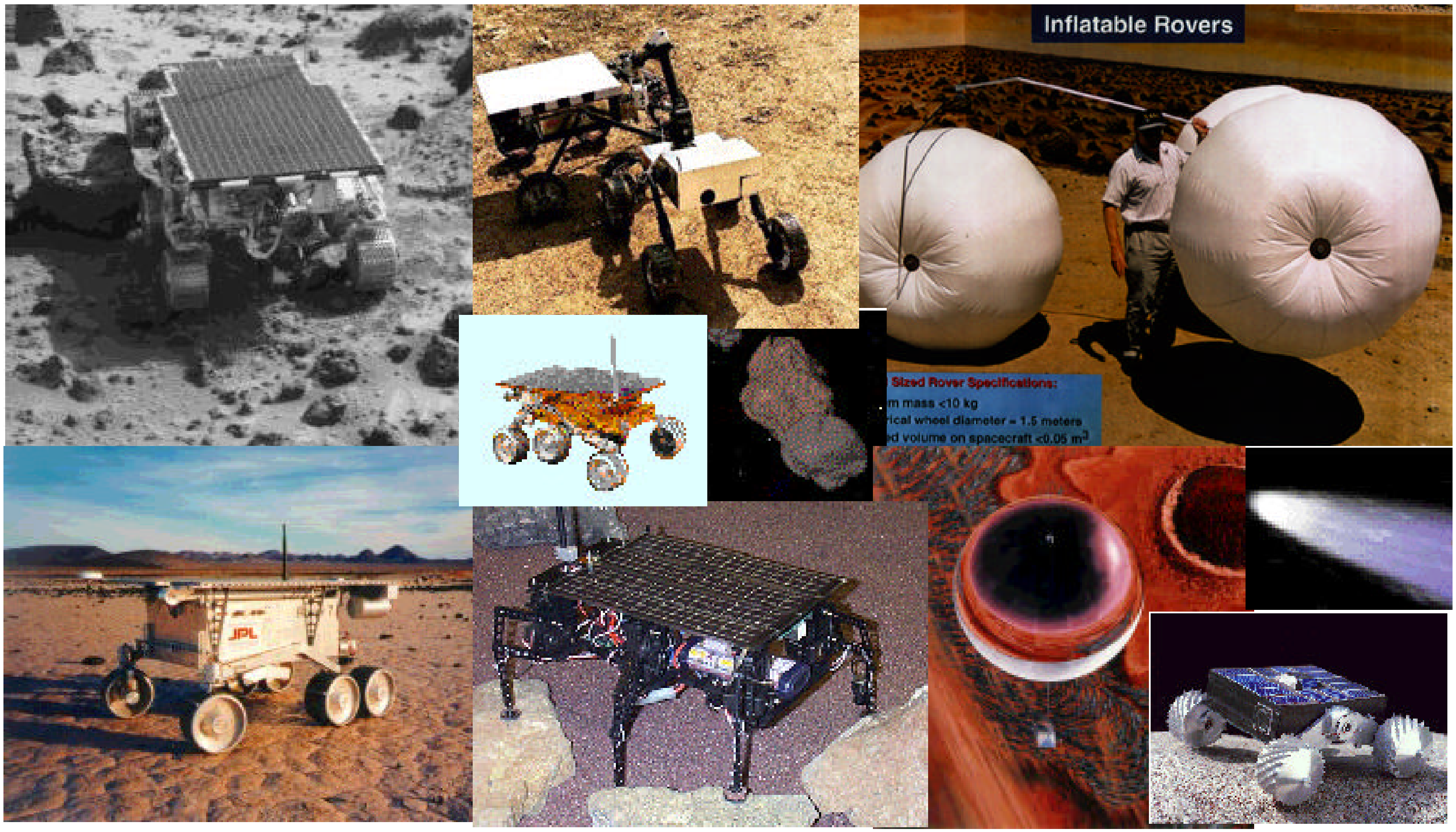
Rover technology at JPL



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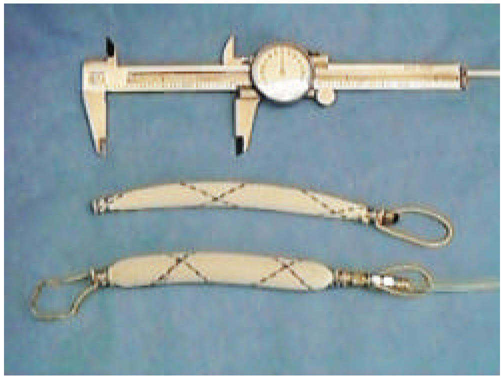
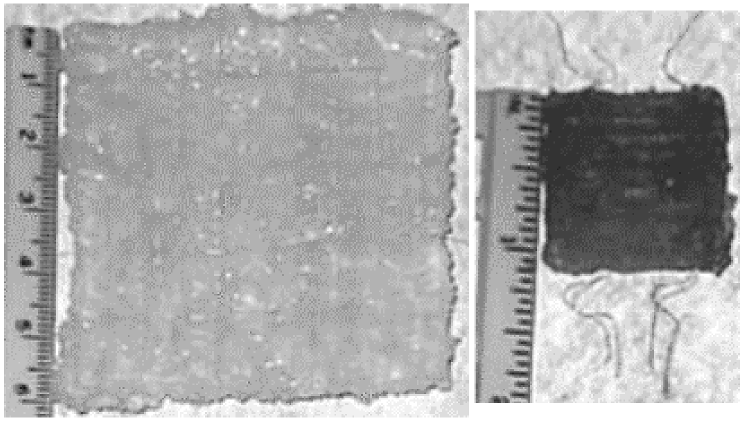
Polymer Actuators

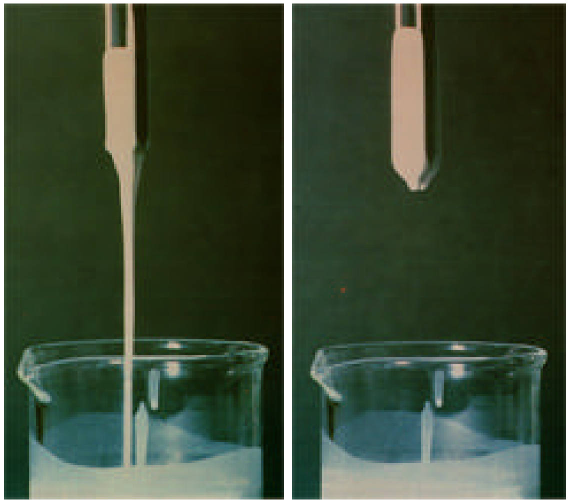


McKibben Artificial Muscles
Air Pressure activation (Hannaford, B.U. Washington)

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



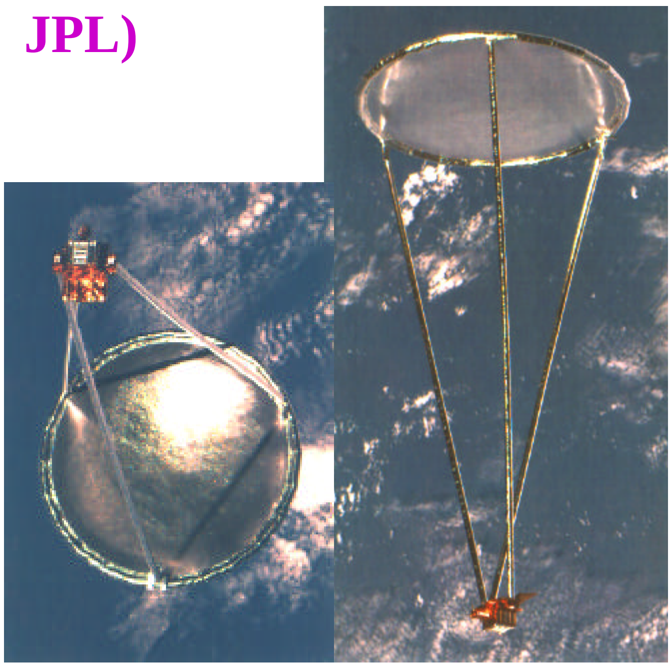
Ionic Gel Polymers
Chemical transduction (P. Calvert, UA)



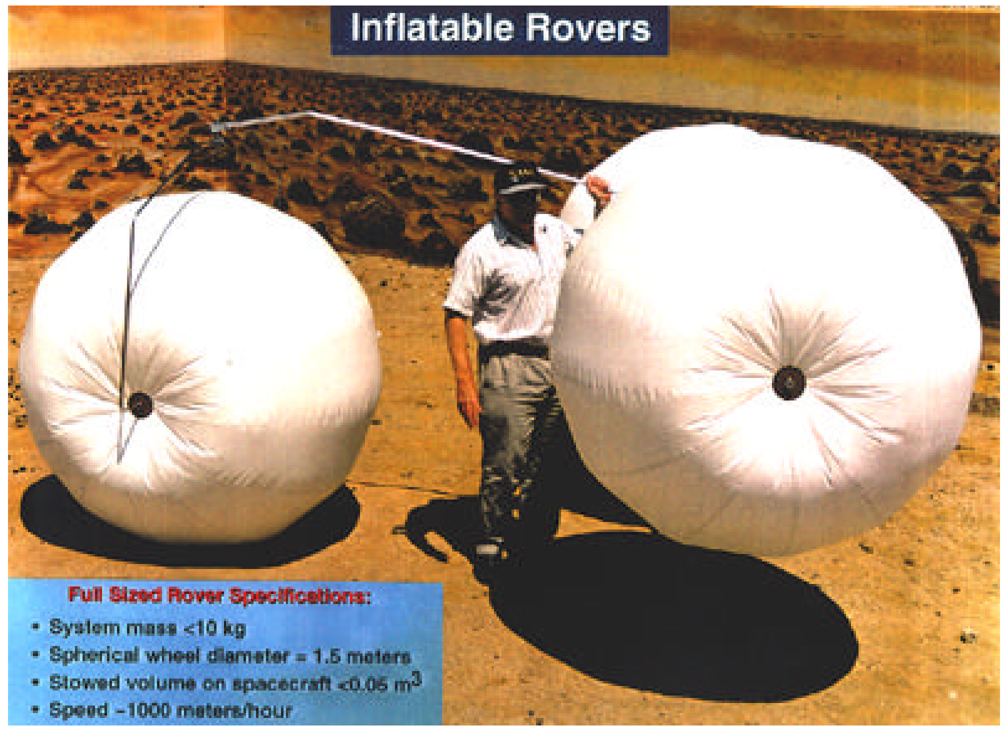
ElectroRheological Fluids
Electrical stimulation (Bayer Silicons Rheobay)

Inflatable structures

Inflatable antennas & telescopes (A. Chmielewski, JPL)



Inflatable vehicles (Jack Jones, JPL)



BACKGROUND AND MOTIVATION

- NASA is using actuation devices for many space applications.
- There is an increasing need for miniature, inexpensive, light and low power actuators.
- Existing transducing type actuators such as piezoceramics are inducing limited displacement levels.
- Electroactive polymers (EAP) ability to induce large displacements offer an enabling technology for unique mechanisms.
- EAP are activated by an electrical field and they can be used to emulate biological muscles.

EAP substituting mechanisms in robots and changing paradigms

- Conventional robots are driven by mechanisms that consist of motors, gears, bearings, etc.
- Electroactive polymers (EAP) offer alternative low mass, low power consuming, inexpensive actuators
- EAP are resilient, fracture tolerant, noiseless actuators.
- These materials allow emulation of biological muscles to produce insect-like robots and other mechanisms.
- Thus, robotic devices can be made that consist of materials only, serving as the structure and the actuators.

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.

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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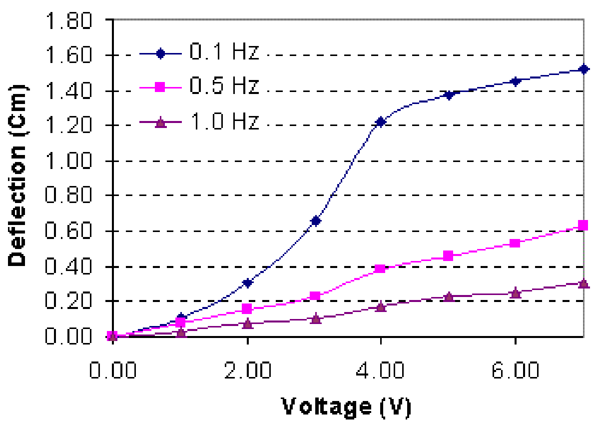
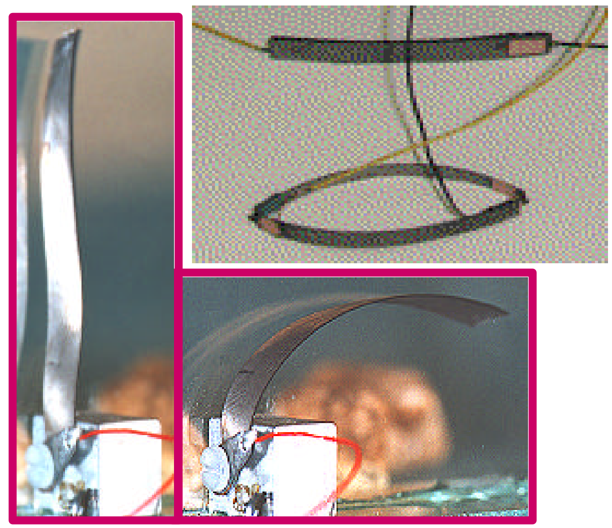
Bending and Longitudinal EAP Actuators





Ion-exchange Polymer membrane Metallic Composite (IPMC) can bend by over 90^{o} under ~3-4V and ~30-50-mW.

31-mm wide, 50-µm thick Electrostatically stricted polymer (ESSP) film extending over 12%

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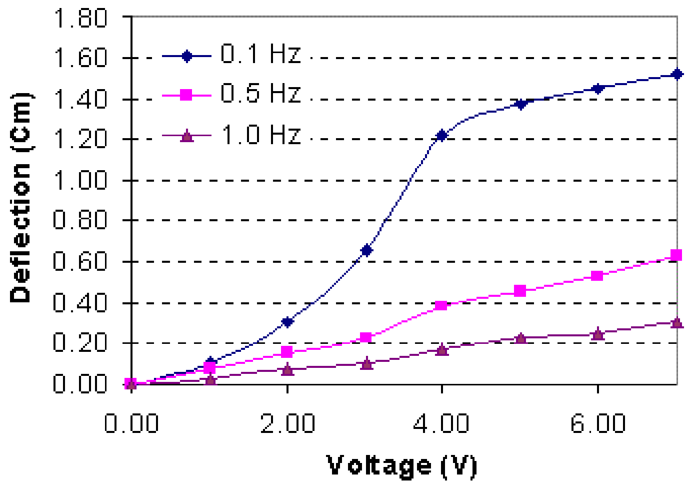
ISSUES ASSOCITED IPMC AS BENDING EAP ACTUAORS



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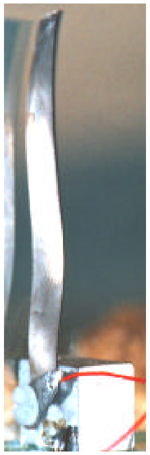
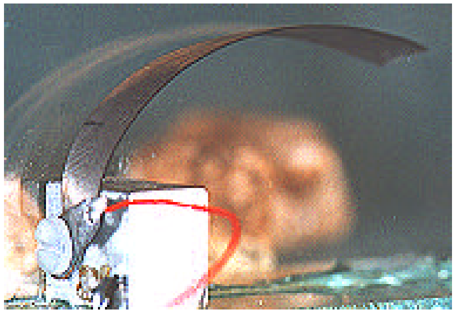


Activated



- Conductive ionic species is responsible for the actuation and it necessitates maintaining moist film.
- The Nafion base IPMC material behaves similar to Teflon and is difficult to bond or to coat.
- Coating IPMC deforms the film and blisters appeared after activation.
- The electrical response of the material is complex and need to be addressed to allow effective control of the electroactivation.

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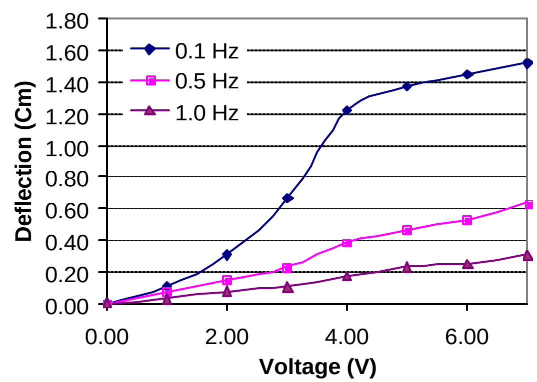
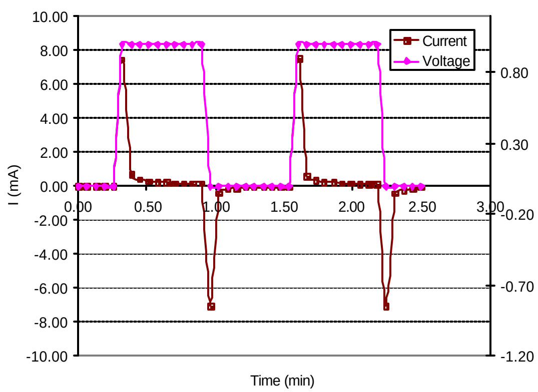
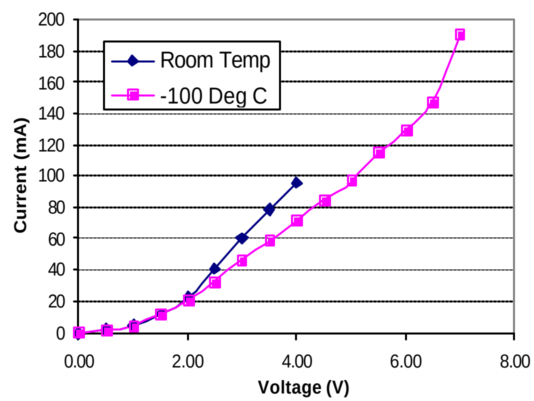
IPMC AS EAP BENDING ACTUATOR



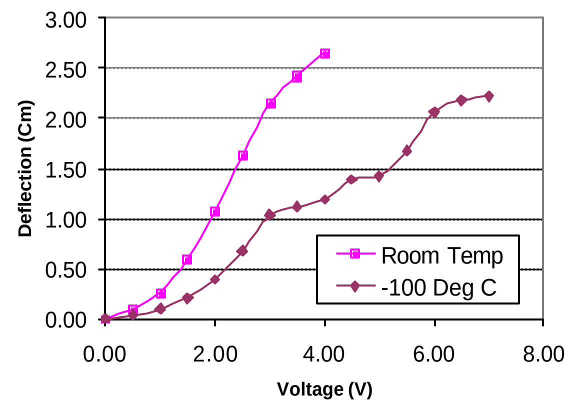
Charging capability



Higher resistance at Low Temp



Response at Cryovac



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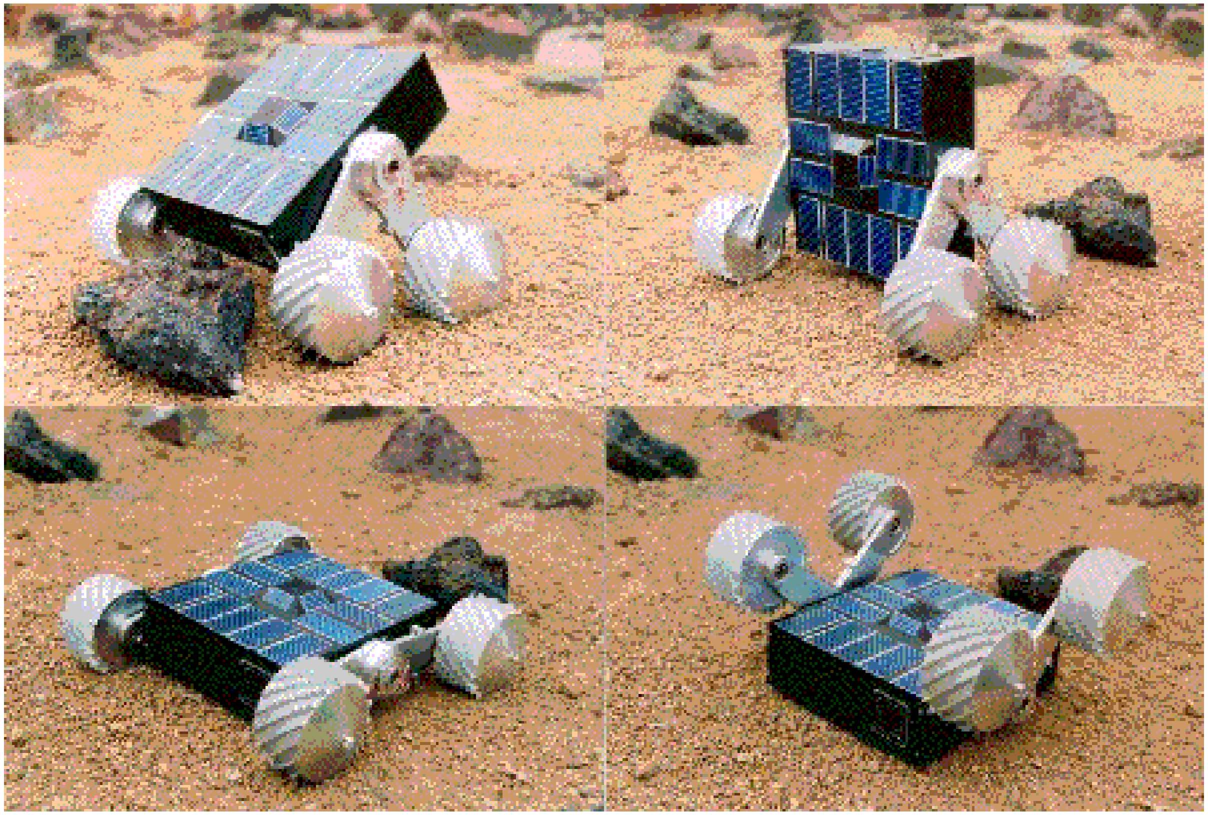
Nanorover in action



Nanorover - miniature rover to be launched in 2002
as part of the MUSES-CN mission to an asteroid.

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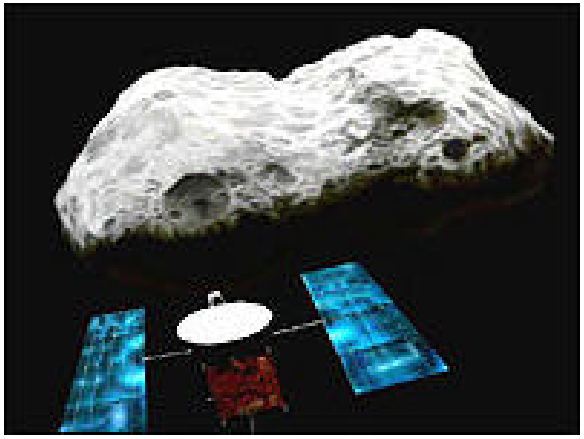
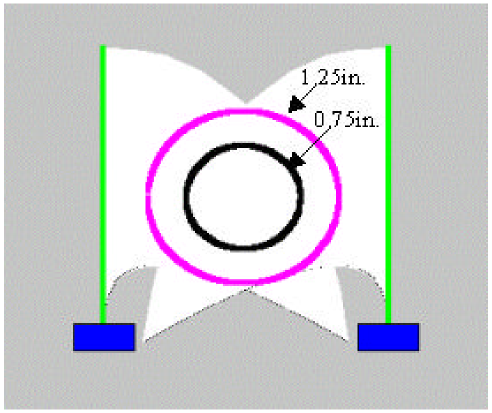
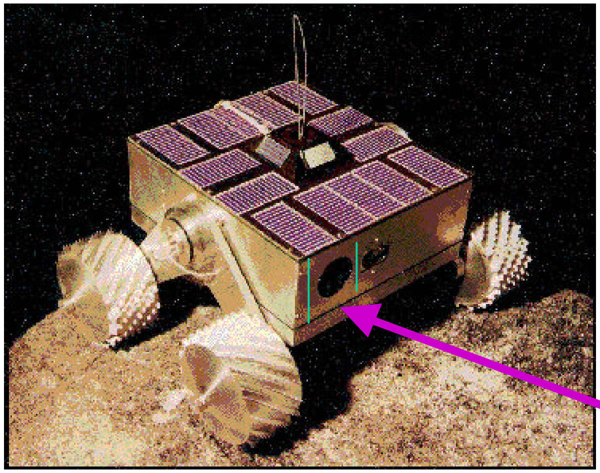
MUSES-CN Mission, the Nanorover and the EAP dust-wiper

- The MUSES-CN mission is planed for launch to an Asteroid in 2002.
- A probe will be dropped on the asteroid and blast-off dust.
- The imaging capability of the Nanorover will be affected by the dust.
- Pair of EAP wipers was basedlined to remove the dust.





Simulated window and 2 side dust wipers



Imaging window

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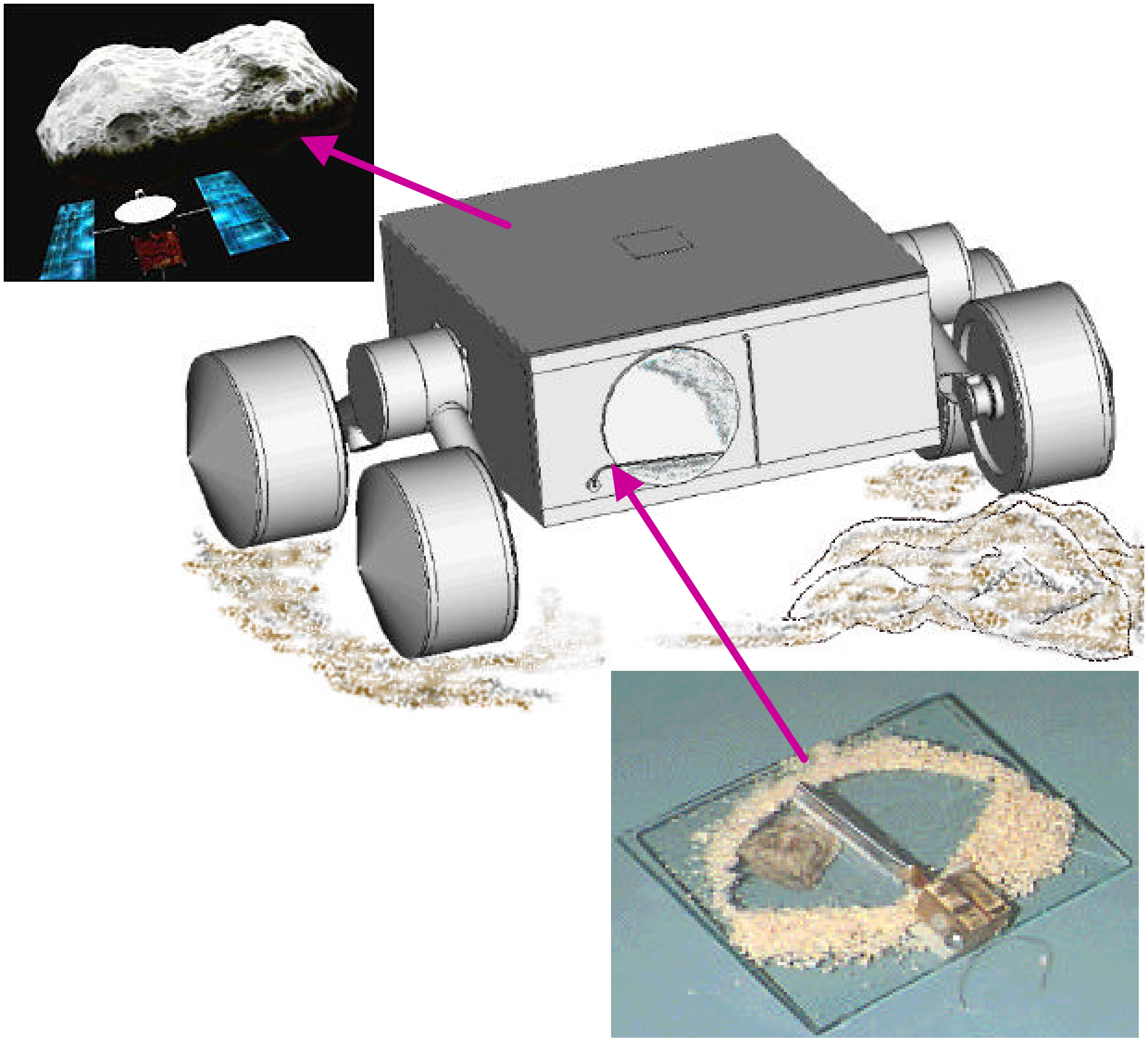
MUSES-CN Nanorover EAP Dust Wiper



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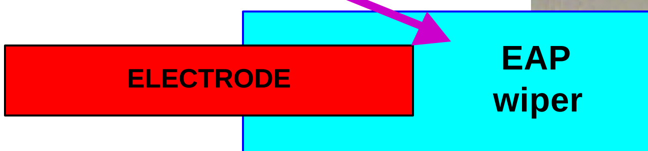
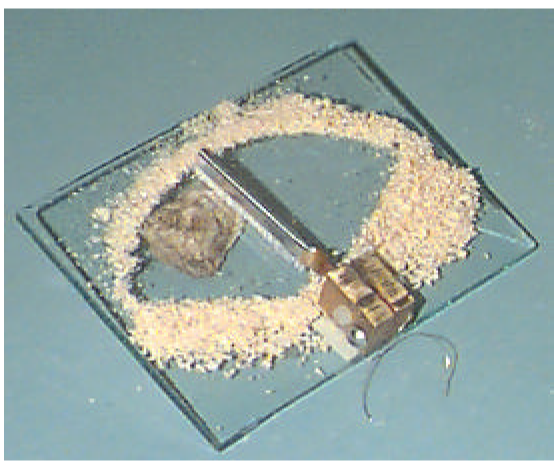
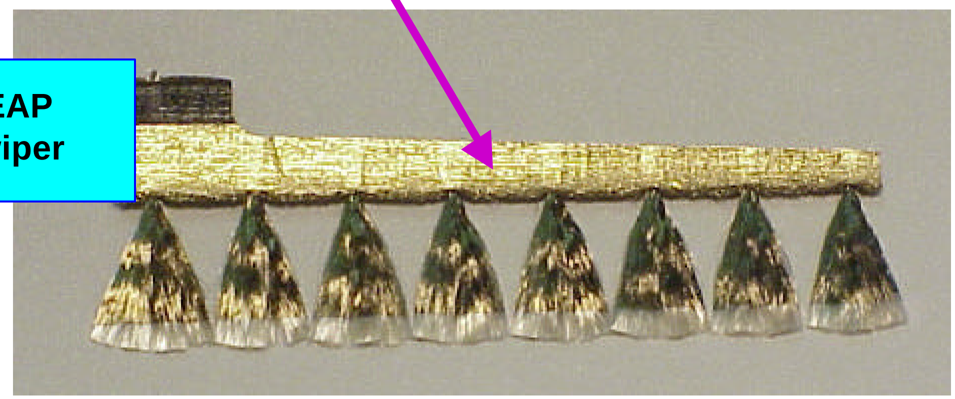
Dust wiper activated by EAP using wiper blade attachment

Actuated by 1-3 volts

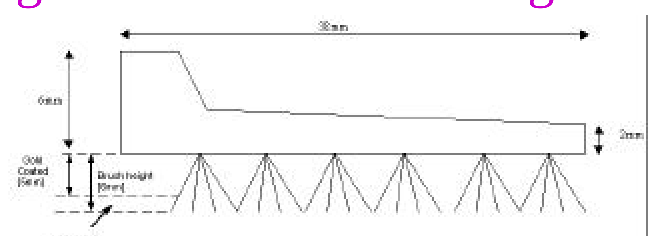
Biased with 1-2KV for dust repulsion







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



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

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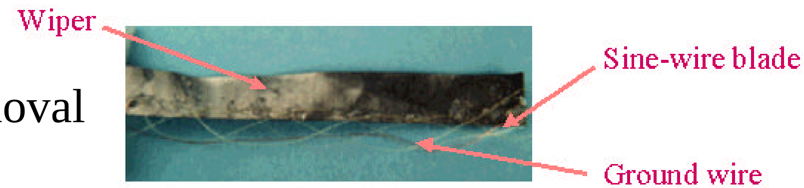
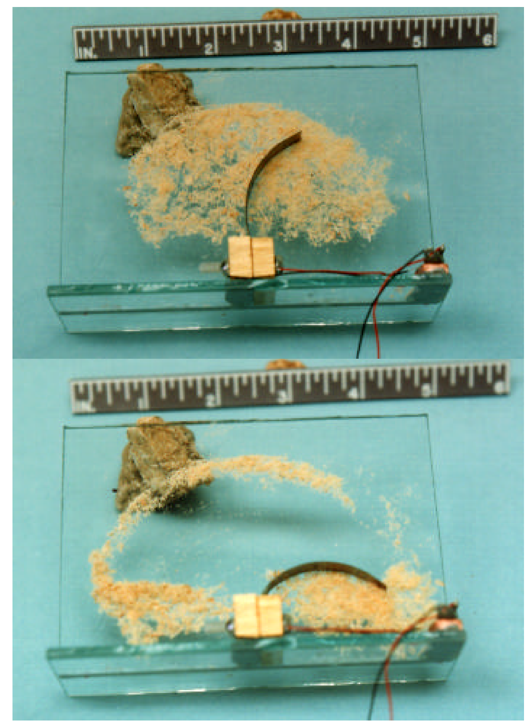
Electroactive Polymers (EAP) Actuators Technology Transfer to MUSES-CN

EAP surface wiper for dust removal



- Driven by low voltage (1-5V) bending-EAP is offering resilient, low-mass, miser, large displacement actuators.
- Bending EAP was shown to operate effectively down to -100°C.
- The technology rapidly emerged from basic research to the level that it address the critical issue of dust removal.
- EAP dust wiper was baselined for the optical/IR window of the MUSES-CN mission's NanoRover.
- Limitations of the EAP actuator are still challenges to the flight application of this technology.



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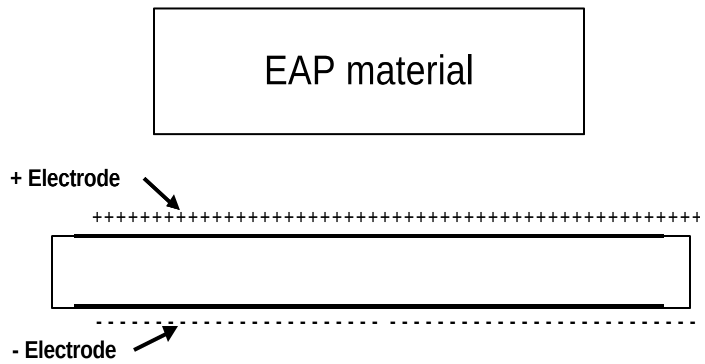
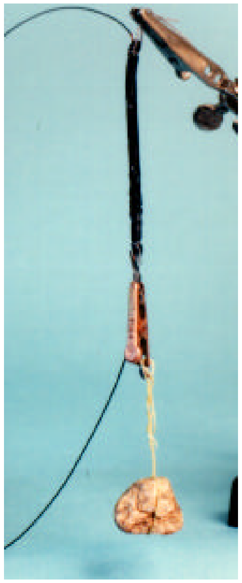
Challenges and solutions to the application of IPMC as bending actuators

Challenge	Solution
Fluorinate base - difficult to bond	Pre-etching (LaRC)
Sensitive to dehydration (~5-min)	Etching and coating (NASA-LaRC)
Electroding points cause leakage	Effective compact electroding method was developed
Off-axis bending actuation	Use of load (e.g., wiper) to constrain the free end
Most bending occurs near the poles	Improve the metal layer uniformity
Electrolysis occurs at >1.23-V in Na+/Pt	• Minimize voltage • Use IPMC with gold electrodes and cations based on – Li^+ – Perfluorocarboxylate with tetra-n-butylammonium (ONRI)
• Survive -155°C to +125°C • Operate at -125°C to + 60°C	IPMC was demonstrated to operate at -140°C
Need to remove a spectrum of dust sizes in the range of >3μm	• Use effective wiper-blade design (ESLI, San Diego, CA) • Apply high bias voltage to repel the dust
Reverse bending under DC voltage	Limit application to dynamic/controlled operations
Developed coating is permeable	• Alternative polymeric coating • Metallic Self-Assembled Monolayer overcoat
No established quality assurance	• Use short beam/film • Efforts are underway to tackle the critical issues
Residual deformation	Still a challenge

LONGITUDINAL EAP ACTUATOR

Under electro-activation, an EAP film with electrodes on both surfaces expands laterally.





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

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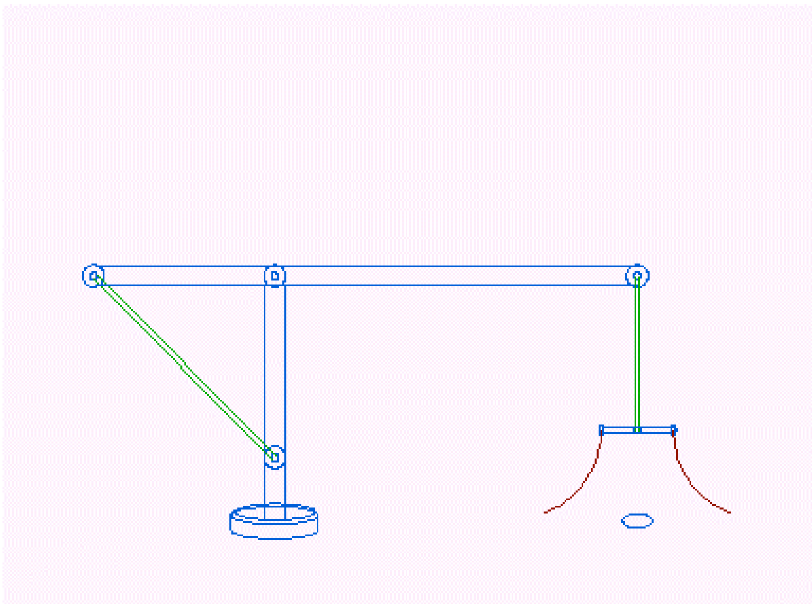
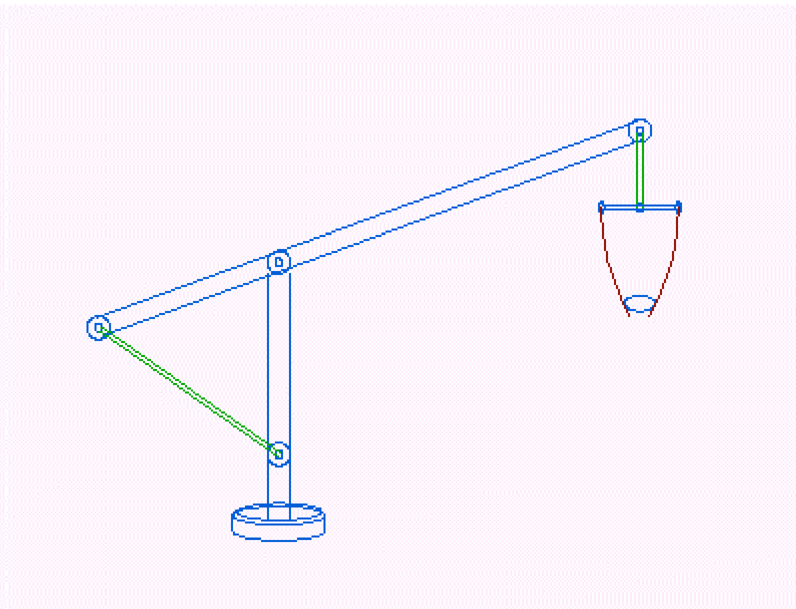
EAP ROBOTIC ARM FOR SAMPLE HANDLING AND MANIPULATION

Simulation





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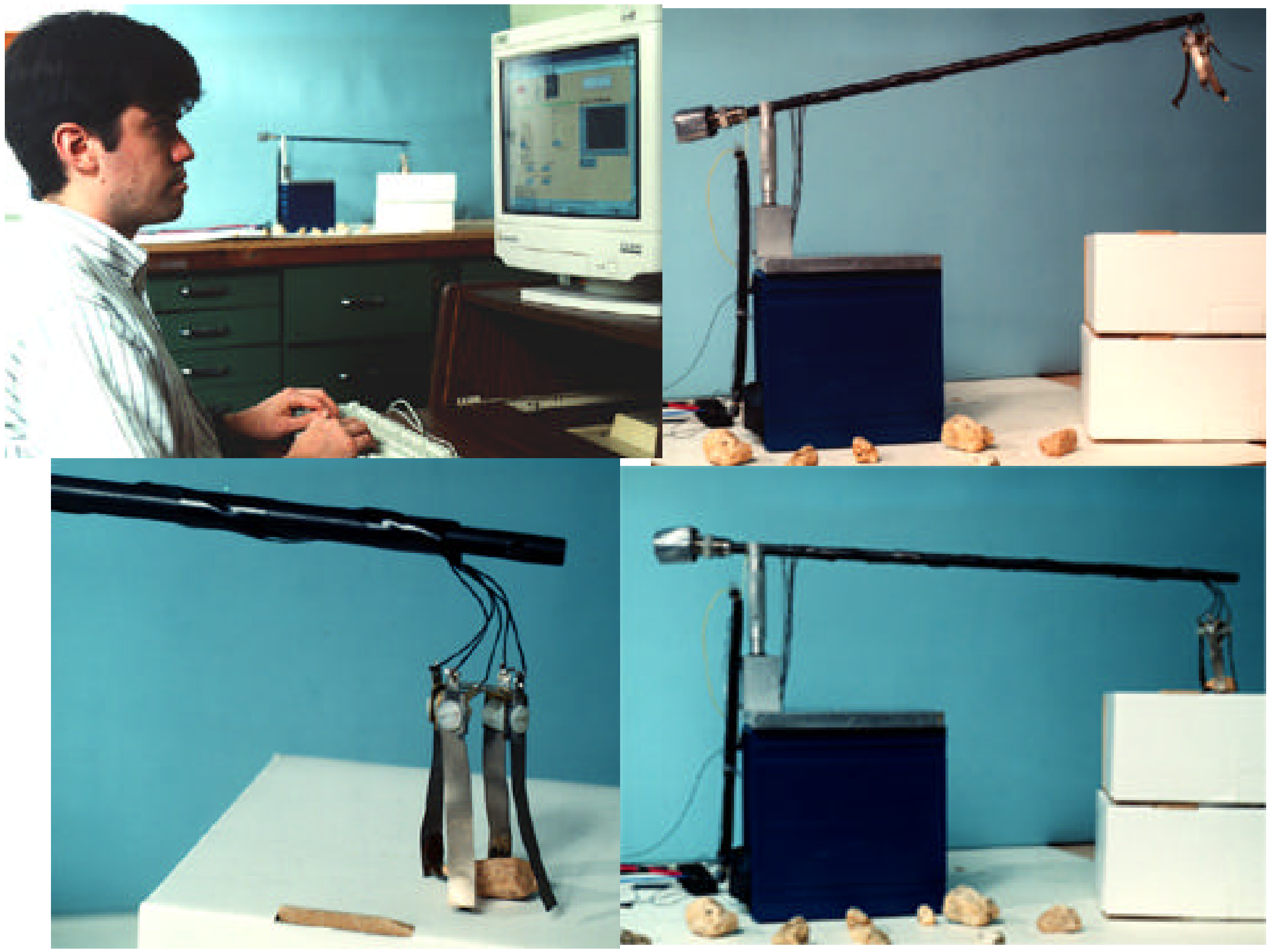
Robotic arm

A computer controlled arm with longitudinal EAP actuator serving as the lifter and bending EAP fingers as the gripper

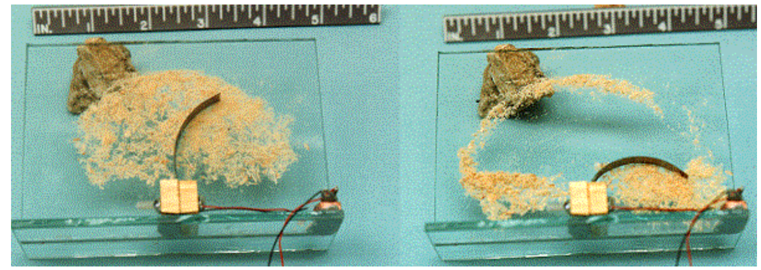


Electroactive Polymer (EAP) Actuators

Applications

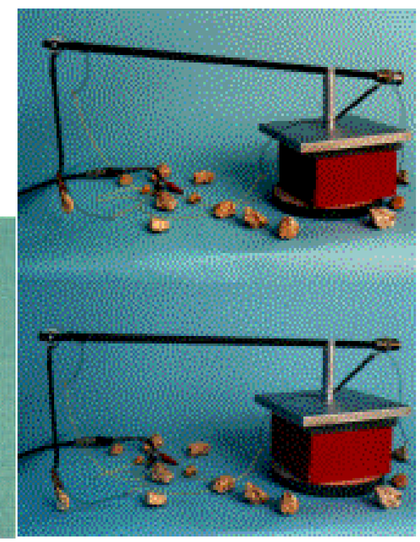
Dust wiper

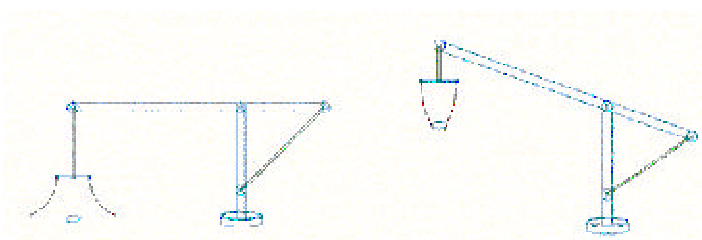
A bending EAP is used to develop a dust wiper

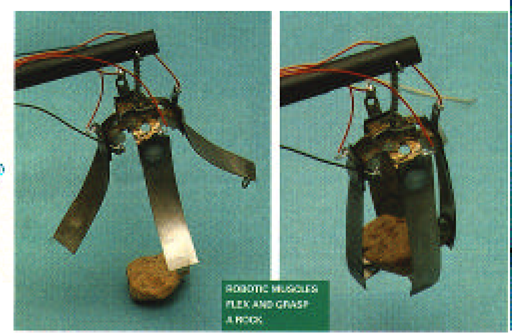


Miniature robotic arm

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







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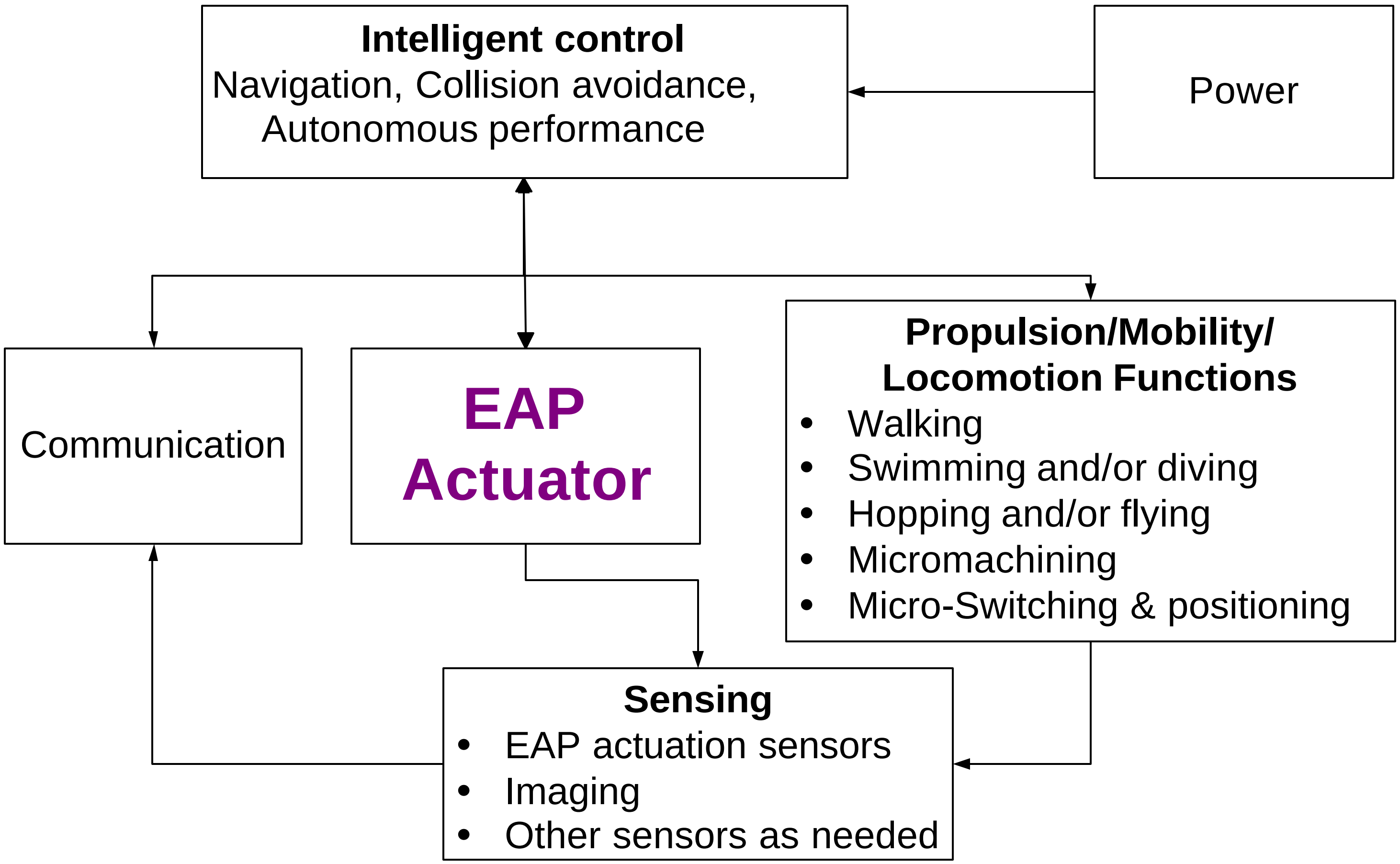
ELEMENTS OF AN EAP ACTUATED ROBOTS



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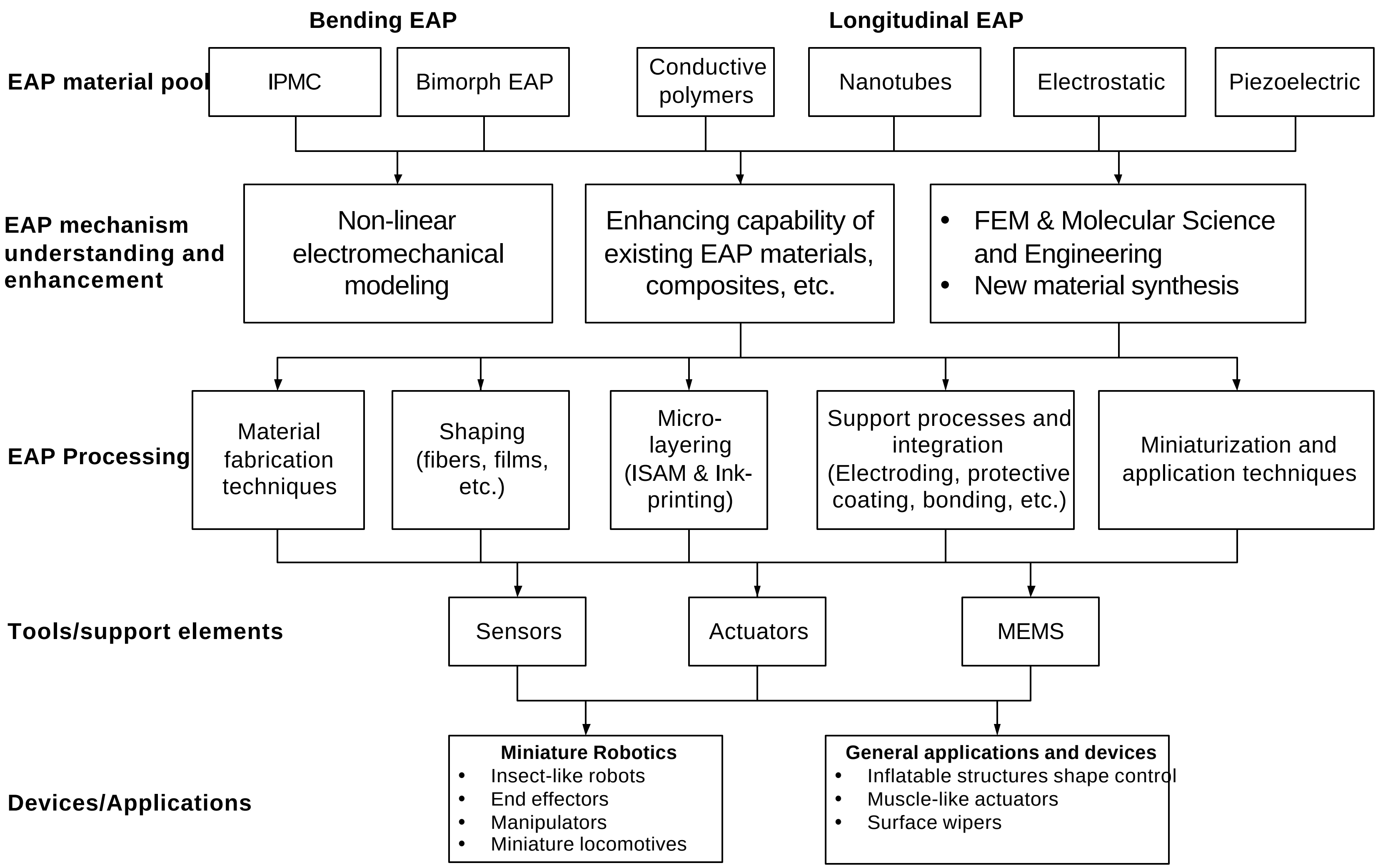
EAP infrastructure



Wet (Ionic) Electroactive Polymers

Actuator type	Principle	Advantages	Disadvantages	Reported types
Ionic Conductive Polymers (ICP)	Materials containing solvated ions that cause swelling in response to an applied voltage.	Use low voltage	Need surface protection to operate in dry environment	Polypyrrole, Polyethylenedioxythiophene, Poly(p-phenylene vinylene)s, Polyaniline, and Polythiophenes.
Ionic gels	Generally, activated by a chemical reaction (changing from acid ← => base increasing density and swelling, respectively.	• Potentially capable of matching the force and energy density of biological muscles	Operates very slowly and would require very thin layers and new type of electrodes to become practical	
Ion-Exchange Polymer Metal Composites (IPMC)	Bending is stimulated in IPMC, where the base polymer provides channels for mobility of positive ions in a fixed network of negative ions on interconnected clusters	• Activated by low voltage • Provides significant bending	• Operates at low frequency. • Sensitive to dehydration and developed coating is ineffective. • Subject to permanent deformation under DC • Subject to hydrolysis above 1.03V	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
Carbon Nanotubes	Using nanometer size tubes ionically activated. Showed induced stains of < 1% along the length and ~300% laterally.	• Potentially provide superior work/cycle & mechanical stresses. • Carbon offers high thermal stability towards >1000 °C.	Expensive. Difficulty to produce in large quantities.	Carbon

Dry Electroactive Polymers

Actuator type	Principle	Advantages	Disadvantages	Reportec types
Ferroelectric Polymers	PVDF is involved with large dielectric loss. Recent introduction of electron radiation in P(VDF-TrFE) copolymer introduced defects into the crystalline structure dramatically lowering the dielectric losses.	• Demonstrates electrostrictive behavior • The relatively high elastic modulus offers high mechanical energy density • Induces relatively large strain (~5%) [being considered for sonar transducers]. • This permits AC switching with a lot less generated heat.	Requires high voltage (~150 MV/m)	Electron radiated P(VDF-TrF
Electro-Statically Stricted Polymer (ESSP) Actuators	Polymers with low elastic stiffness and high dielectric constant can be used to induce large actuation strain by subjecting them to an electrostatic field where Coulomb forces between electrodes to squeeze and thus stretch the material	• Large displacements reaching levels of 200% • Rapid response	• Requires large voltage. • Obtaining large displacements compromises the actuation force	• Silicone • Polyurethai

Current EAP
Advantages and disadvantages

EAP type	Advantages	Disadvantages
Dry	• Can operate in room conditions for a long time • Can respond at very high frequencies • Provide large actuation forces	• Requires high voltages • Compromise between strain and stress is needed
Wet (Ionic)	• Provides mostly bending actuation (longitudinal mechanisms can be articulated) • Large bending displacements • Sustain hydrolysis at >1.23-V • Requires low voltage	• Does not hold strain under DC voltage • Operates at low frequencies (several Hertz) • Bending EAP presents a vary low actuation force

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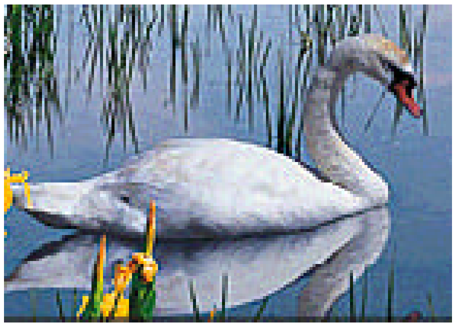
BIOLOGICALLY INSPIRED ROBOTICS

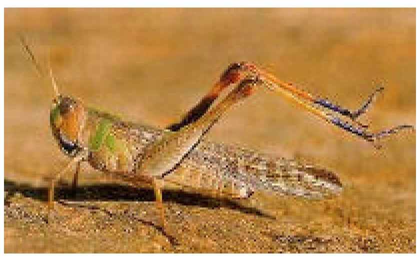
MULTI-TASKING IN-SITU MISSIONS USING SCALABLE AUTONOMOUS ROBOTS FOR COLONIZED PLANETARY EXPLORATION

Multiple locomotion capabilities

Flying, walking, swimming & diving



Hopping, flying, crawling & digging



Coordinated robotics

Models for EAP Actuated Flexible Robots

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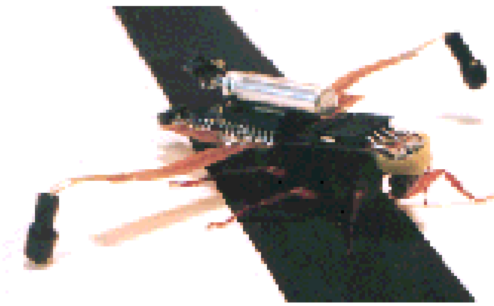
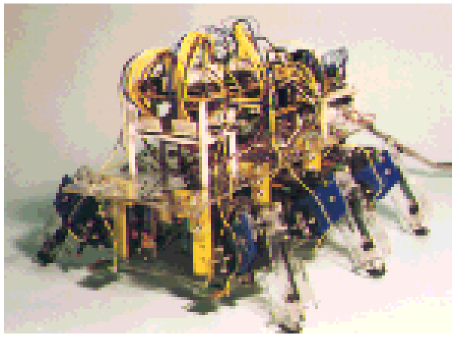
INSECTS AS WORKHORSES AND ROBOTS

- Insects were used by various researchers (e.g., University of Tokyo, Japan) as locomotives to carry backpack of wireless electronics.
- EAP offer the potential of making insect-like robot to replace the "real thing".



Cricket

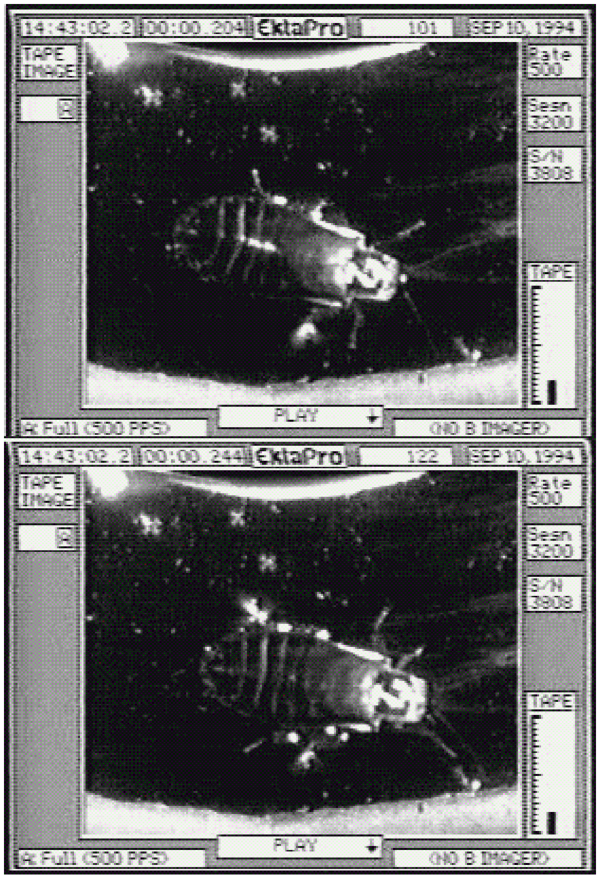


Spider

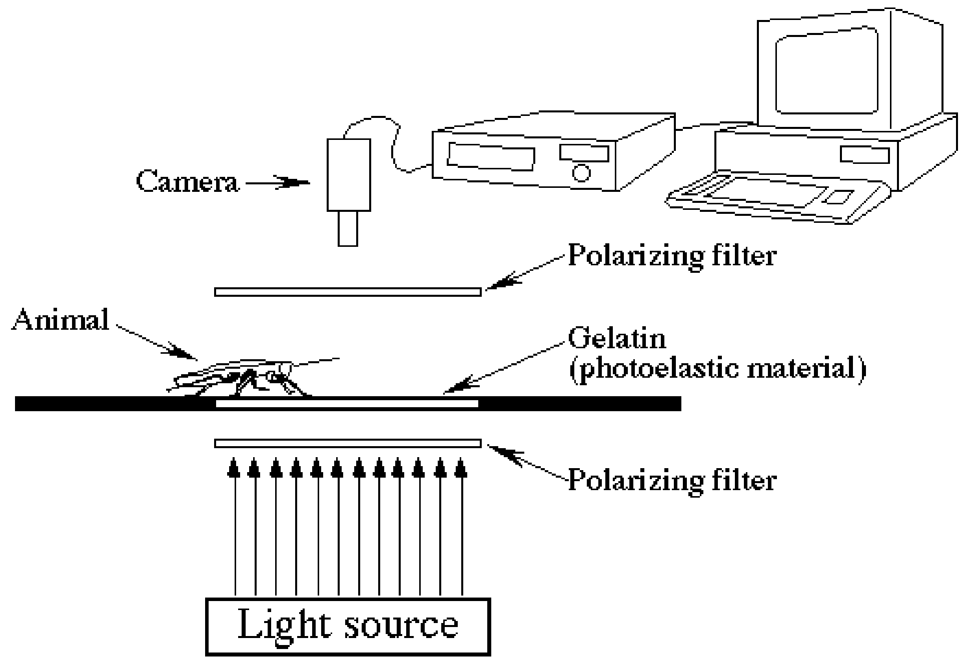
Cockroach

Reference: http://www.leopard.t.u-tokyo.ac.jp/

Insect walking process*



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



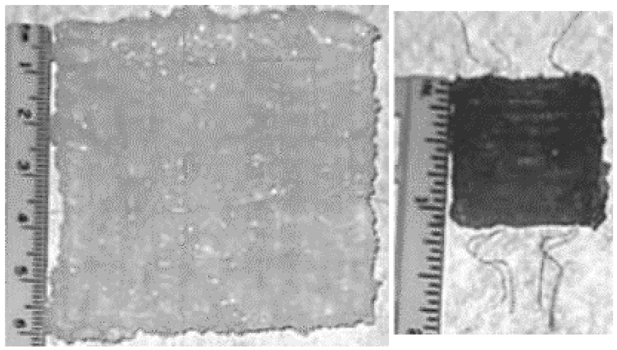
* Robert Full, Berkeley U.
Ref: http://rjf2.biol.berkeley.edu/Full_Lab/FL_Publications/PB_Posters/94ASZ_Turning/94ASZ_Turning.html

Key challenge to EAP

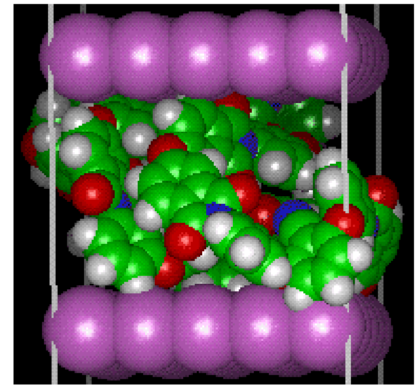
EAP materials induce low actuation force

New EAP materials and processes

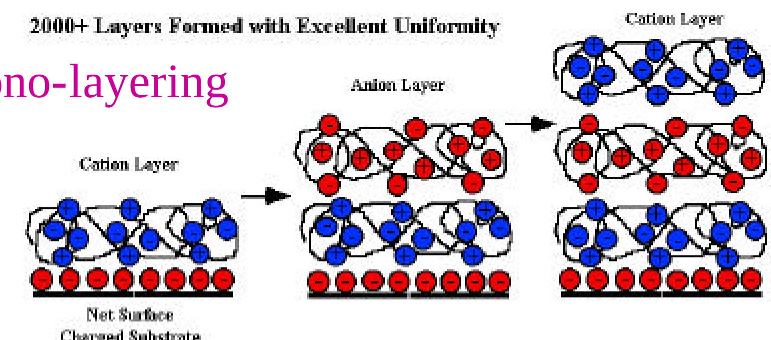
New materials:
Ionic gel EAP



New material design tools:
Computational chemistry

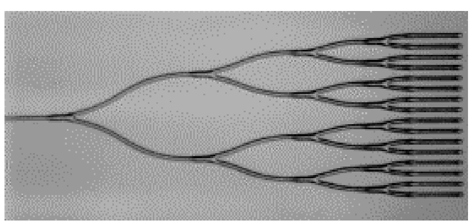


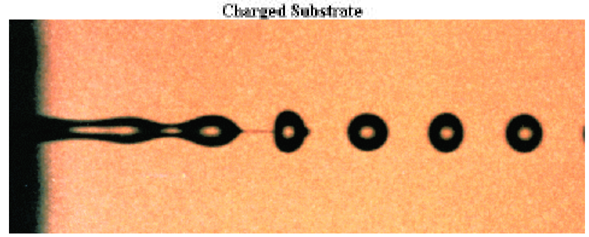
Ionic Self-Assembled mono-layering

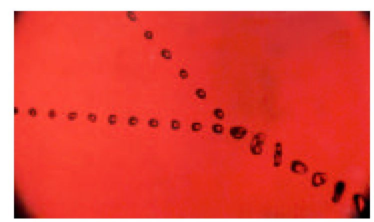


Micro-fabrication techniques:

Ink-printing







100-mm Waveguide

50-mm drops jet

International technical forums for interaction and collaboration

- SPIE Smart Structures and Materials Symposium - EAP Actuators and Devices Conference - held at Newport Beach, CA, on March 1-2, 1999

- MRS Conference - Symposium FF: Electroactive Polymers - held in Boston, MA, on Nov. 29 to Dec. 3, 1999

- The first WW-EAP Newsletter issue was published electronically in June, 1999
  http//ndeaa.jpl.nasa.gov/nasa-nde/lommas/eap/WW-EAP-Newsletter.html

- On Nov. 19, 1999 - An electronic communication platform (newsgroup) was formed eap-request@artemis.arc.nasa.gov "subscribe eap"

- 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

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 to serve as a forum for collaboration among the developers and users of the technology.

Call for Papers and Announcement

Electro-active Polymer Actuators and Devices (EAPAD) (ss04)

Part of SPIE's 6th Annual International Symposium on Smart Structures and Materials
1–5 March 1999 • Newport Beach Marriott Hotel and Tennis Club • Newport Beach, California USA

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

Cochair: **Mohsen Shahinpoor,** Univ. of New Mexico

Program Committee: **Carol Becker,** Space and Naval Warfare Systems Ctr., San Diego; **Paul D. Calvert,** Univ. of Arizona; **Richard O. Claus,** Virginia Polytechnic Institute and State Univ.; **Danilo De Rossi,** Univ. degli Studi di Pisa (Italy); **Michael Goldfarb,** Vanderbilt Univ.; **Chang Liu,** Univ. of Illinois/Urbana-Champaign; **Ajit K. Mal,** Univ. of California/Los Angeles; **Edward McCullough,** Boeing North American; **Jon S. McElvain,** UNIAX Corp.; **Yoshihito Osada,** Hokkaido Univ. (Japan); **Toribio F. Otero,** Univ. del Pais Vasco (Spain); **Francis Patten,** DARPA; **Joycelyn O. Simpson,** NASA Langley Research Ctr.; Minoru Taya, Univ. of Washington; **David B. Wallace,** MicroFab Technologies, Inc.

For many years, electro-active ceramic and shape memory alloys have been the primary source of actuation materials for smart structures and drive mechanisms. Numerous applications have been reported including robotics, active damping, vibration isolation, manipulation, articulation, and many other functions. Electro-active polymers (EAP) received relatively little attention due to small number of available materials as well as their limited observed actuation capability.

In recent years, new and effective EAP materials have emerged that are changing the view of these materials capability and potential. Their key attraction is their ability to emulate biological muscles and their ability to induce strong levels of displacement strain. Recent studies of their operation at low temperatures and vacuum have been very promising, making them potential actuators for space mechanisms. Unique robotic components and MEMS devices have been reported, where EAP provided the actuation or mechanism of mobility. Insect-like mechanisms are becoming a possible reality and new enabling technologies are now feasible. This conference is seeking to turn the spotlight on these materials and their applications as well as to increase the recognition of EAP as viable option for smart structures.

Papers are solicited on but not limited to the following topics:

- electro-active polymers (EAP) materials and their characteristics
- muscles, actuators and sensors based on conducting (electronic and ionic) polymers
- MEMS and robotic applications of electro-active polymer actuators
- control, biomechanics and neuromuscular techniques, and applications of EAPs
- medical applications of artificial muscles, biotelemetry, cochlear implants,
- intelligent and adaptive processing of biological sensory information and implantable devices
- support electro-active polymer technology, including organic batteries
- models, analysis and simulation of EAP
- mechano-chemo-electrical devices as a reverse property of the artificial muscles (electro-chemo-mechanical devices)
- biomechanics and bio-mimetic application including walking, crawling, swimming and flying micro-devices.
- miniature robo-creatures including: flies, insects, worms, etc.

Abstracts and papers submitted MUST show an explicit connection to smart structures and materials in both the abstract and the main text in order to be considered. This connection can be either direct (the technique would be used directly in a smart structure) or indirect (the technique can be used to help create something that would be used directly in a smart structure).

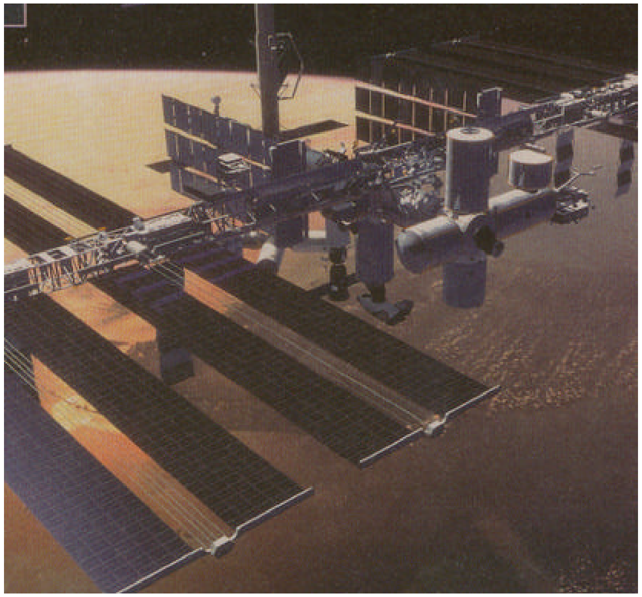
Abstract Due Date: 3 August 1998
Manuscript Due Date: 1February 1999

SPIE—The International Society for Optical Engineering

SPIE is an international technical society dedicated to advancing engineering, scientific, and commercial applications of optical, photonic, imaging, electronic, and optoelectronic technologies. Its members are engineers, scientists, and users interested in the development and reduction to practice of these technologies. SPIE provides the means for communicating new developments and applications information to the engineering, scientific, and user communities through its publications, symposia, education programs, and online electronic information services.

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.

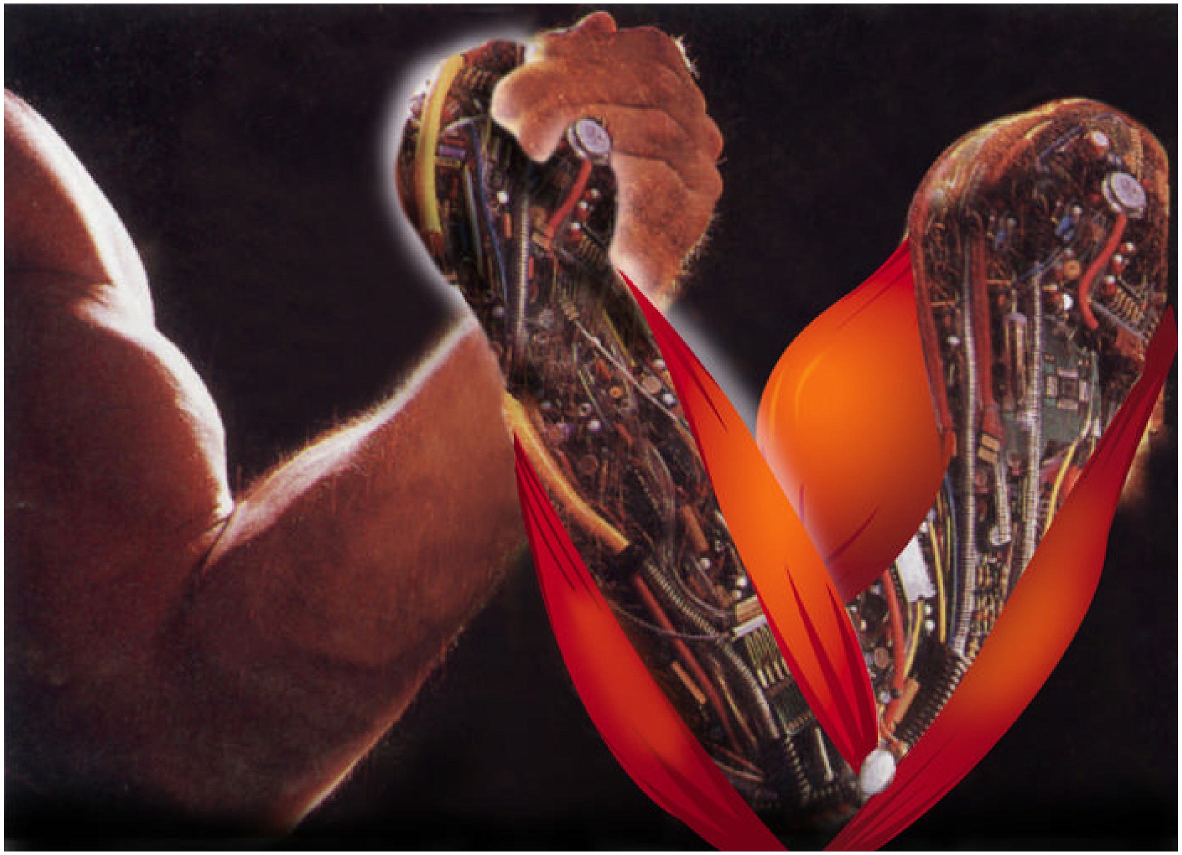


PI: Suzanne L. B. Woll, Ph.D. Non-metallic Materials Technology Boeing Phantom Works, (425) 965-0672 Renton

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 a NASA task, several 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 SPIE conference, 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



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