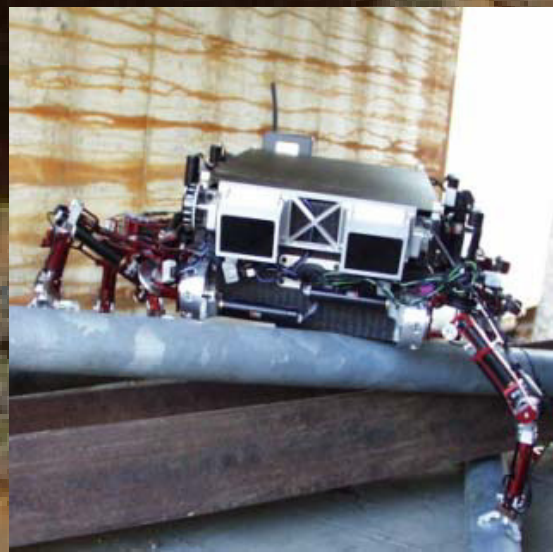
Biomimetics as a model for inspiring human innovation

Yoseph Bar-Cohen, PhD

Senior Research Scientist & Group Supervisor, JPL/NASA, yosi@jpl.nasa.gov

http://eap.jpl.nasa.gov

http://ndeaa.jpl.nasa.gov



http//ndeaa.jpl.nasa.gov

Jet Propulsion Laboratory
California Institute of Technology

+ View the NASA Portal

Search JPL

JPL HOME | EARTH | SOLAR SYSTEM | STARS & GALAXIES | TECHNOLOGY

NDEAA

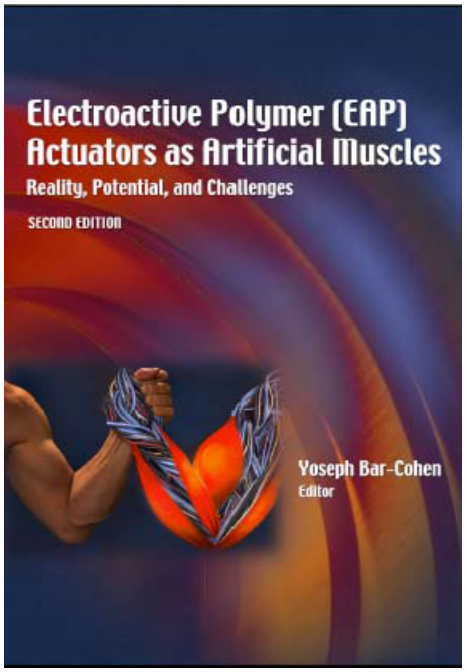
Nondestructive Evaluation and Advanced Actuators Technologies

The JPL's Nondestructive Evaluation and Advanced Actuators (NDEAA) Technologies lab was established by Dr. Yoseph Bar-Cohen in May 1991 and it is part of his JPL's Advanced Technologies Group. The Group members are Dr. Jack B. Aldrich (Caltech Postdoc Scholar), Dr. Mircea Badescu, Dr. Xiaoqi Bao, Dr. Zensheu Chang, Ayoola Olorunsola and , Dr. Stewart Sherrit. Other scientists that are working in his NDEAA Lab include Dr. Shyh-Shiuh Lih , and Jay (Jiunnjenq) J. Wu . The NDEAA lab is one of the JPL Unique Facilities and it is involved with innovative research and development (R&D) for space applications and technology transfer to other fields. The topics of R&D include novel actuators (mostly using electroactive ceramics and polymers), transducers, sensors, robotic mechanisms and NDE methods. The group conducts analytical modeling, mechanisms development, performance testing and characterization as well as analysis that involve mechanical, electrical, magnetic and thermal parameters and interactions. Between Jan. 1, 2000 and Jul. 2, 2001, this NDEAA webhub had 1,000,007 (crossed the one million) total hits with 87,082 unique hits and by Sept. 3, 2001 it crossed the one hundred thousand (100,006) unique hits. The highest hits per day was recorded on March 9, 2005, where 9063 total hits and 3626 unique hits were recorded. This lab has been the subject of many articles in the news media. **The NDEAA lab is involved with a broad range of R&D topics as described in the following clickable icons. The photos of the NDEAA members are clickable to their biography**

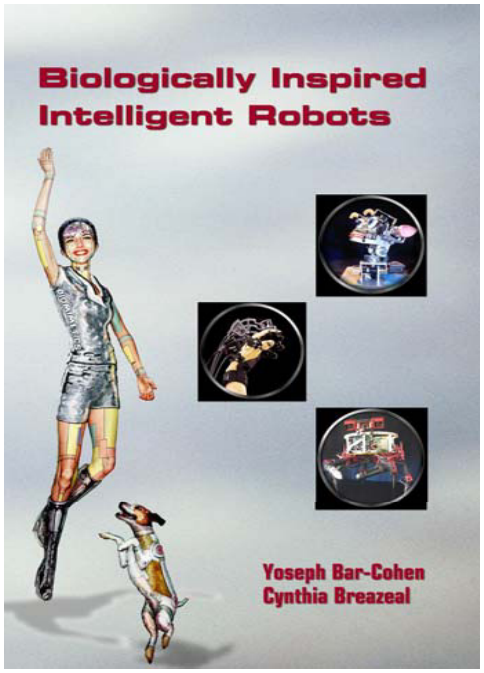
Dr. Y. Bar-Cohen, Supervisor, Advanced Tech. Group & Senior Research Scientist | Dr. Jack Aldrich | Dr. Mircea Badescu | Dr. Xiaoqi Bao | Dr. Zensheu Chang | Dr. Shyh-Shiuh Lih | Ayoola K Olorunsola | Dr. Stewart Sherrit | Jay (Jiunnjenq) J. Wu

The developed mechanisms are driven by elastic waves, mechanical vibrations and/or electroactive materials. Examples of these mechanisms include ultrasonic and surface acoustic wave motors and piezoelectric pumps that are driven by traveling flexural waves. Recently, an ultrasonic/sonic driller/corer (USDC) was developed and shown to have enormous potential for sampling, deep drilling, probing, sensing and in situ analysis making it a Lab-on-a-Drill. In parallel, electroactive polymers are being investigated for use as actuators (artificial muscles). Other technologies that are being explored include Haptic interfaces for robotics and Human Muscle Enhancers -- high power ultrasound for medical treatment, ferroelectric source that generates various radiations and charged particles, biomimetic technologies and geophysical probing using elastic waves. In addition to planetary applications, these devices and mechanisms have potential terrestrial applications for medical, commercial, and others. These efforts involve technical cooperation with scientists and engineers at various universities, research institutes, medical centers and industry in the USA and internationally. Further, the Nov. 2001 issue of the NASA Tech Briefs covered Dr. Bar-Cohen and NDEAA in a "Who's Who in NASA" article.

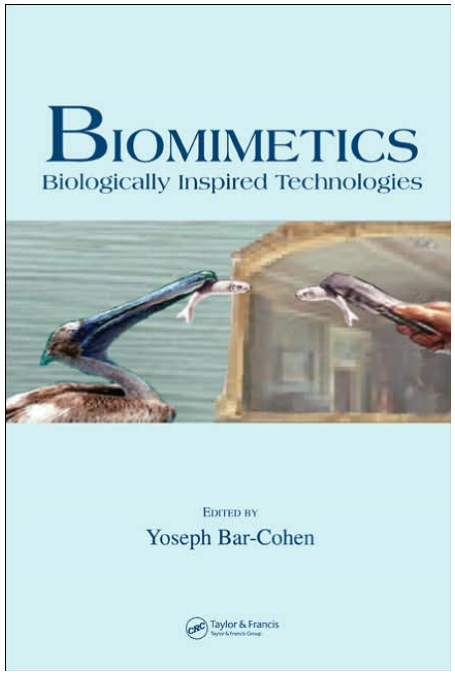
Related books



1st Edition (03/2001)
2nd Edition (03/2004)



March 2003



November 2005

http://ndeaa.jpl.nasa.gov/nasa-nde/yosi/yosi-books.htm

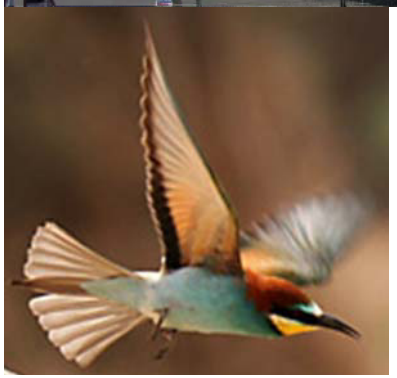
Why mimic nature?

During the Dec. 2004 tsunami, animals run while humans stayed behind unaware of the coming danger.

The woodpecker does not get dizzy after strong tapping on wood

Biology – inspiration of human innovation

The honeycomb is now part of almost every aircraft

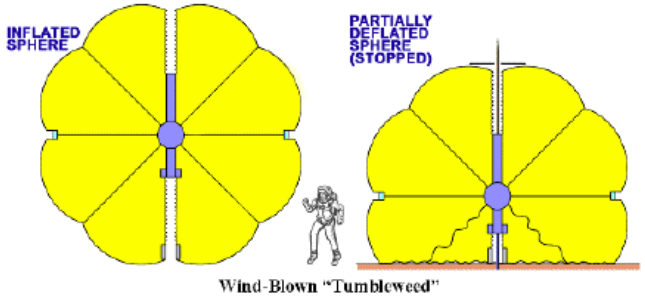


The desire to fly was enabled using aerodynamic principles leading to enormous capabilities

The spider is quite an "engineer". Its web may have inspired the fishing net, fibers, clothing and others.

Shelled creatures inspired human body defense armors

Nature as a model



The tumbleweed as an inspiring structure

Defense strategies including camouflage

Courtesy of William M. Kier, of North Carolina

Courtesy of Roger T. Hanlon, Director, Marine Resources Center, Marine Biological Laboratory, Woods Hole, MA

Octopus adaptive shape, texture and camouflage

Ref: http://www.pbs.org/wnet/nature/octopus/

Nastic structures – plants as a mimicking model

Venus Flytrap *(Dionaea Muscipula)*

Sensitive Fern (*onoclea sensibilis*)

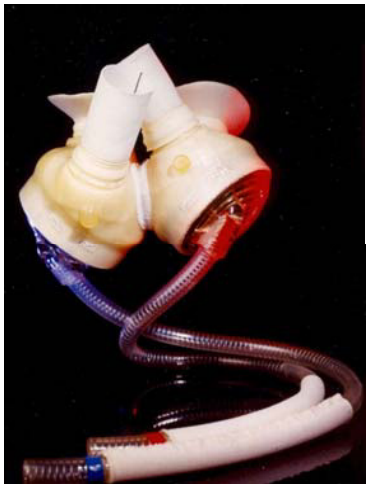
Picher plant (*Sarracenia purpurea*)

Artificial Organs

Augmenting or replacing body organs with artificial mechanisms and devices is increasingly enabled as a result of significant advances in bio-compatible materials, powerful microelectronics, and efficient miniature actuators. Examples include:

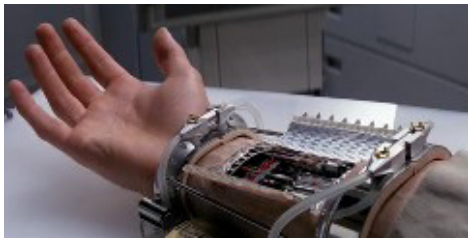
– Artificial organs such as heart, lung, kidney, liver, hip, and others.

– Smart limbs with various degrees of sophistication.



Smart Prosthetics and Human-Machine Interfacing

- Interfacing human and machine is already enabling various important medical applications.
- Using electrodes connected to the brain of a monkey were used to demonstrate control of a robotic arm.
  - In 2004, FDA approved testing the technology in humans at the level of controlling a cursor on a computer monitor using wireless device.
- DARPA has an on going program "Revolutionizing Prosthetics" to develop smart prosthetic hand that can operate and feel as good as the real thing. http://www.darpa.mil/dso/solicitations/prosthesisPIP.htm
- In parallel, under European project called Cyberhand, a highly dexterous, artificial hand and sensory system that may provide patients with active feeling is being developed http://istresults.cordis.lu/index.cfm/section/news/tpl/article/BrowsingType/Features/ID/79407



DARPA funded prosthetic hand
http://bearcreekledger.com/?p=676

The Cyberhand - European artificial hand

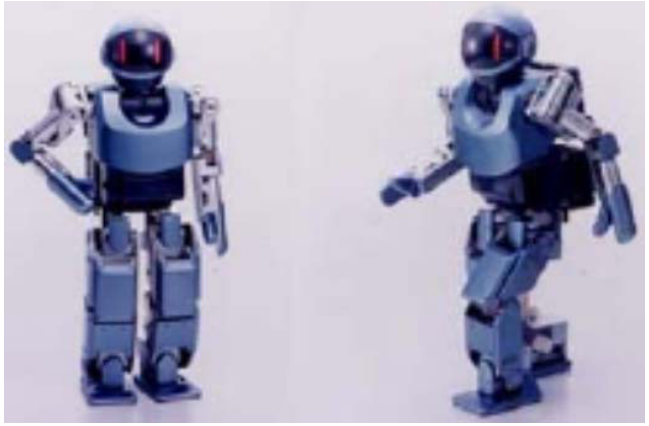
DARPA funded prosthetic arms

- Jesse Sullivan, 59, of Dayton, TN, is the world's first "bionic man".
- Sullivan was a worker who lost both arms in a power-line accident.
- Doctors have "rewired" him using his severed arm nerves in his chest muscles.
- Now his mind actually "senses" his missing hands and he moves his mechanical arm by contracting those muscles.

http://www.msnbc.msn.com/id/13325828/site/newsweek/?GT1=8211

Courtesy of the Rehabilitation Institute of Chicago (RIC)

Smart Toys



Sony's SDR3

Ref: http://world.honda.com/robot/movies/

Honda's Asimo

Ref.: http://www.designboom.com/eng/education/robot.html

AIBO - Sony 2nd Generation ERS-210

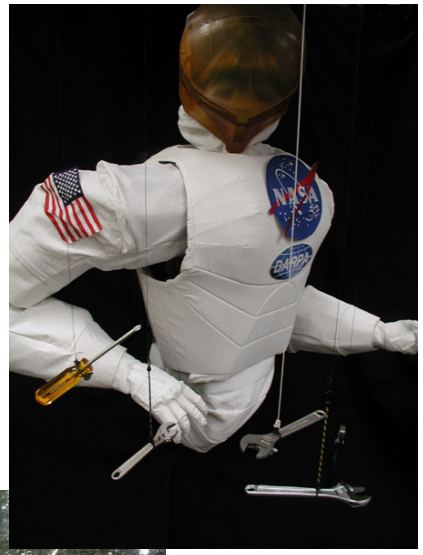
Ref.: http://www.us.aibo.com/ers_210/product.php?cat=aibo

I-Cybie

Ref.: http://www.i-cybie.com

Applications of biomimetic robots

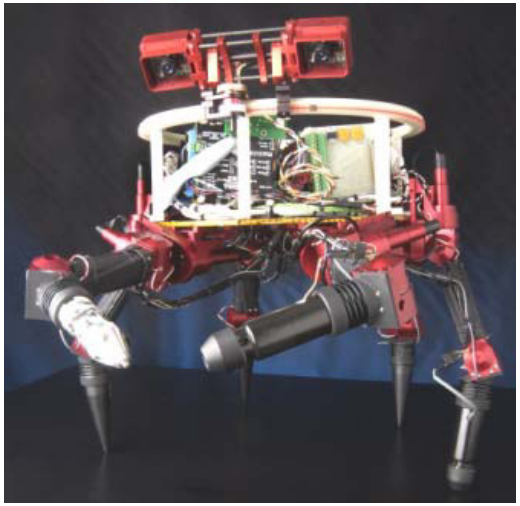
Robonaut



Mattel's Miracle Moves Baby doll making realistic behavior of a baby.

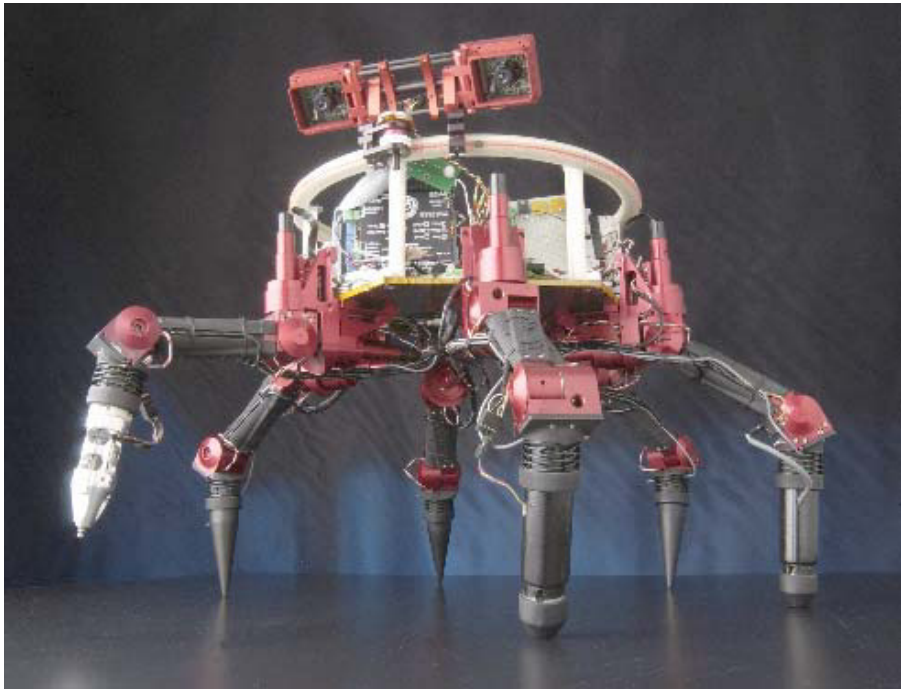
Walking forest machine for complex harvesting tasks (Plustech Oy, Finland) [http://www.plustech.fi/Walking1.html]

Multi-limbed robots LEMUR (Limbed Excursion Mobile Utility Robot) at JPL

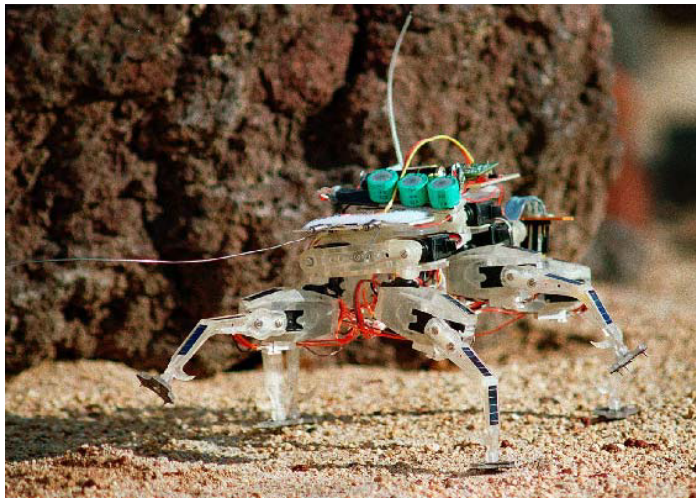


Legged robots at JPL

The crab as a model for walking robots



LEMUR (Limbed Excursion Mobile Utility Robot) - 6-legged robot, Brett Kennedy, JPL



Spider-bot, Robert Hogg, JPL

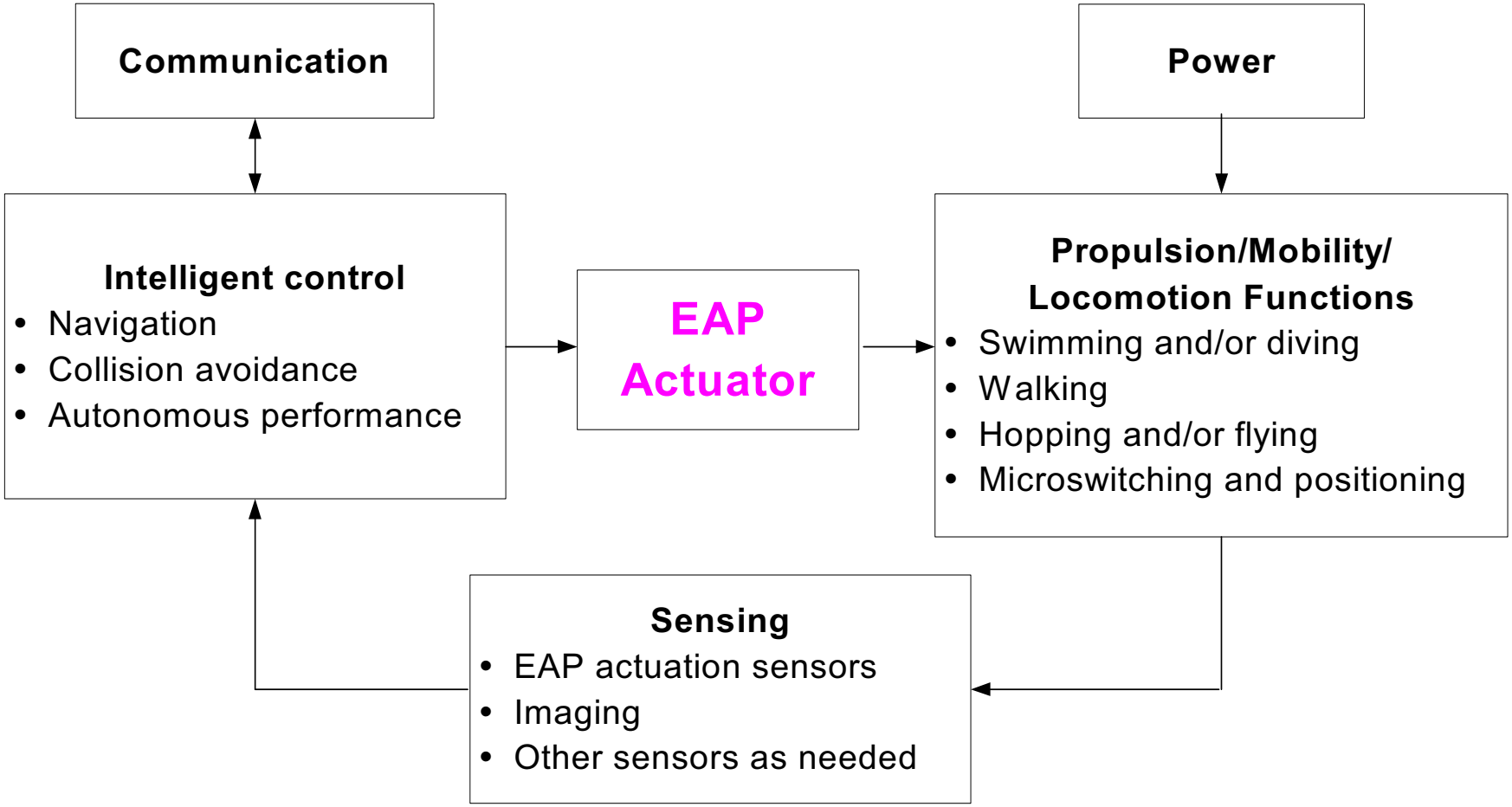
Sociable Robots

Robots that respond to human expressions

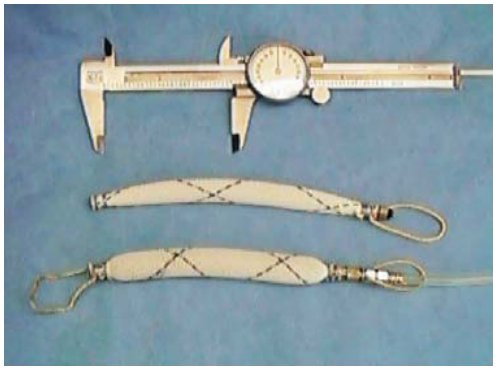
Cynthia Breazeal and her team at MIT talking to her robot Kismet

Ref: C. Breazeal, Designing Sociable Robots. MIT Press, Cambridge, MA (2002)

Elements of an actuated system

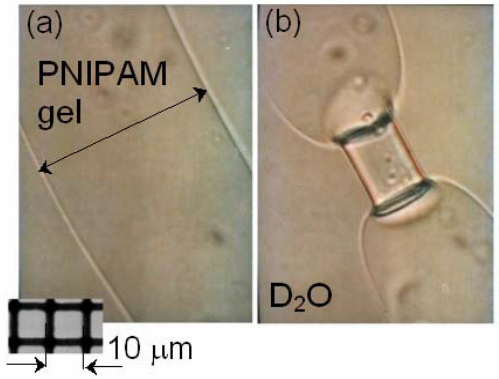


Non-electrical mechanically activated polymers



McKibben Artificial Muscles

Air Pressure activation (Hannaford, B.U. Washington)

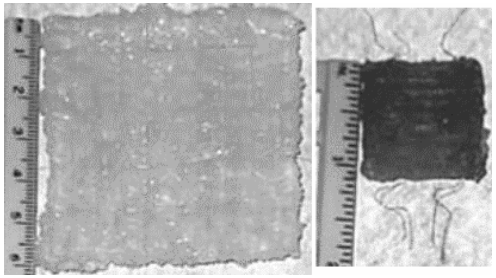


Laser Illuminated Polymer

Light activation (H. Misawa, Japan)

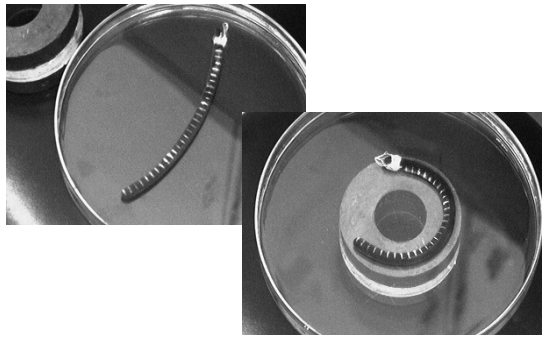
Shape Memory Polymers

Heat/pressure activation (W. Sokolowski, JPL)



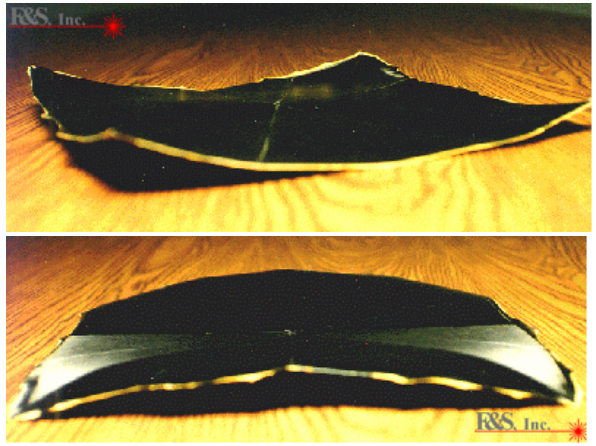
Ionic Gel Polymers

Chemical transduction (P. Calvert, UA)



Ferrogel

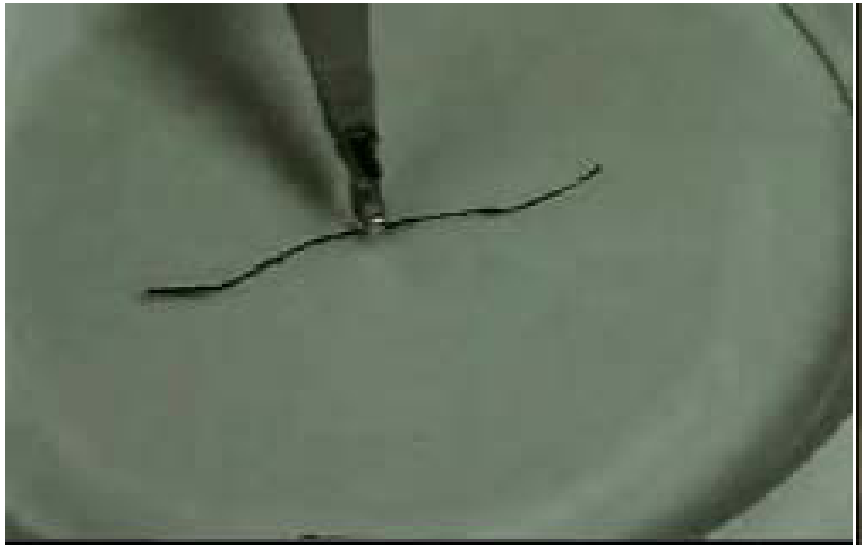
Magnetic Activation (M. Zrinyi, Hungary)



Smart Structures

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

Various active EAP



IPMC made by Keizuke Oguro, ONRI, Japan

Ferroelectric EAP made by Qiming Zhang, Penn State University, USA

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.

Electroactive Polymers (EAP)

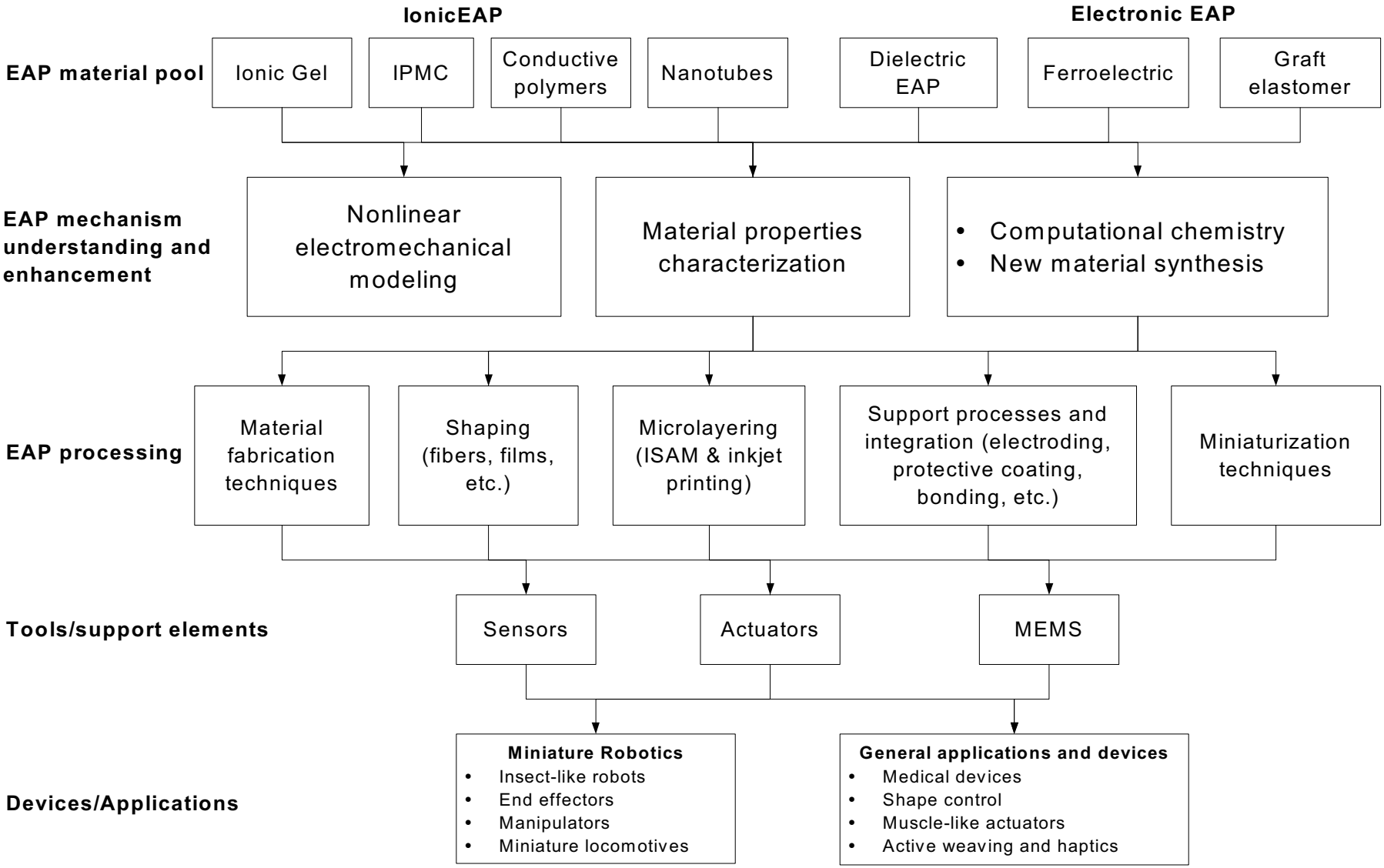
ELECTRONIC EAP

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

IONIC EAP

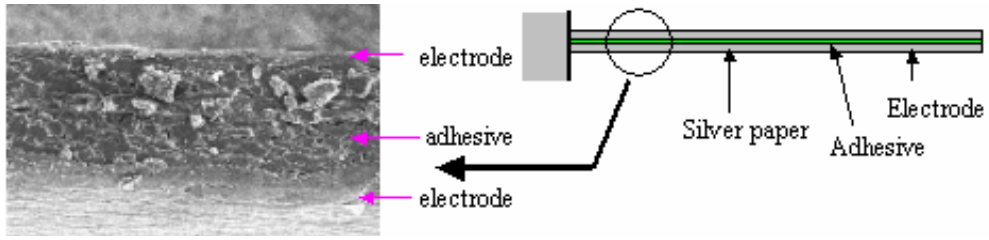
- Carbon Nanotubes (CNT)
- Conductive Polymers (CP)
- ElectroRheological Fluids (ERF)
- Ionic Polymer Gels (IPG)
- Ionic Polymer Metallic Composite (IPMC)

EAP infrastructure



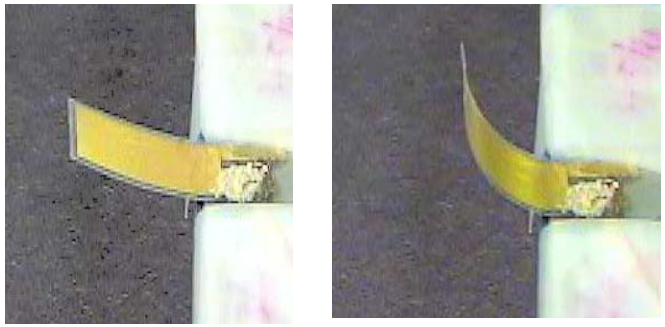
Electronic EAP

ELECTRIC FIELD OR COULOMB FORCES DRIVEN ACTUATORS



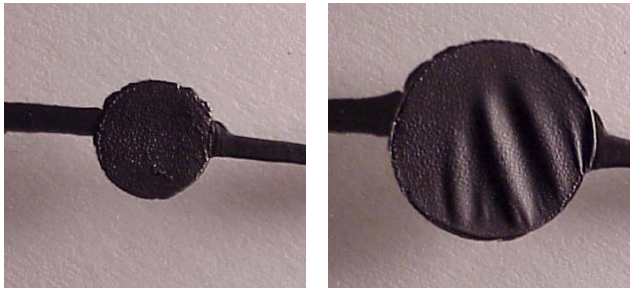
Paper EAP

[J. Kim, Inha University, Korea]



Ferroelectric

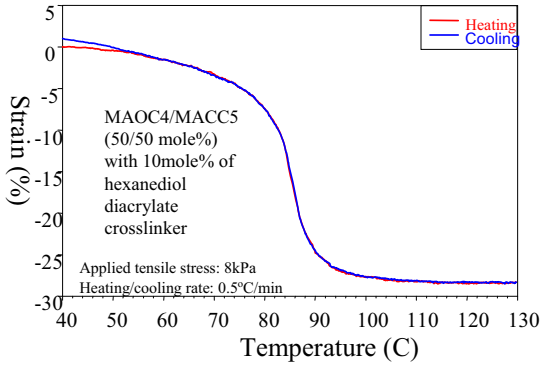
[Q. Zhang, Penn State U.]



Voltage Off **Voltage On**

Dielectric EAP

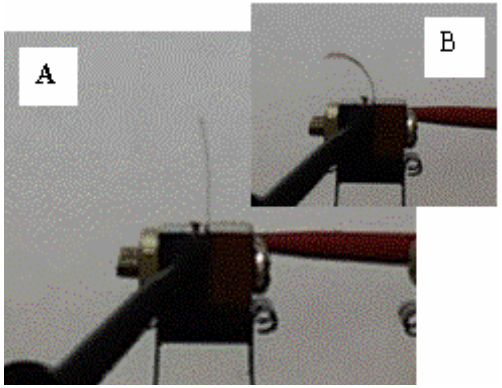
[R. Kornbluh, et al., SRI International]



Liquid crystals

(Piezoelectric and thermo-mechanic)

[B. R. Ratna, NRL]

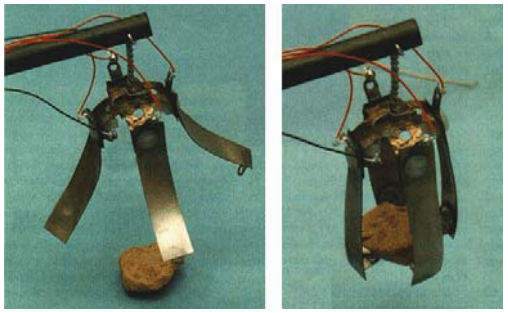


Graft Elastomer

[J. Su, NASA LaRC]

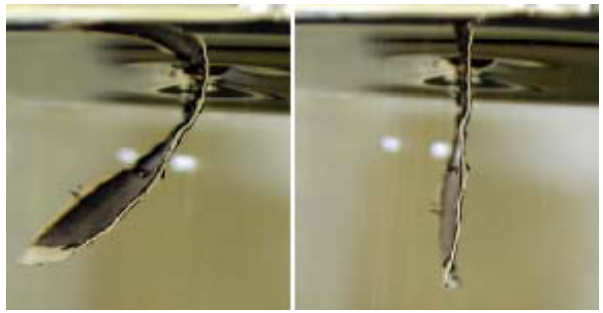
Ionic EAP

Turning chemistry to actuation



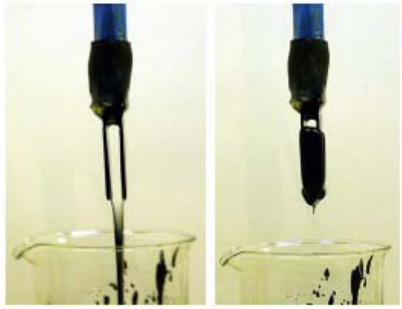
IPMC

[JPL using ONRI, Japan & UNM materials]



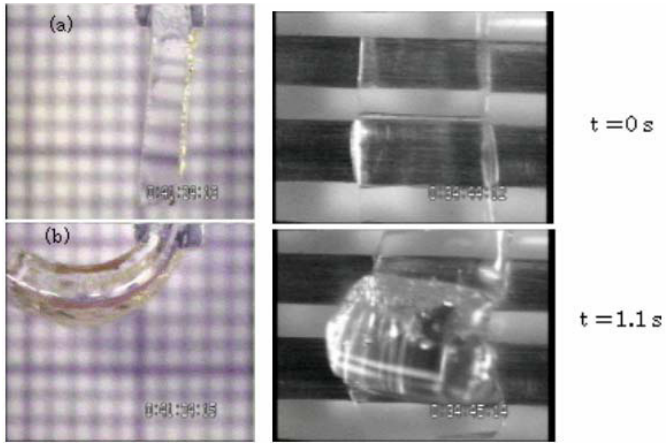
Conductive Polymers

[Made and photographed at JPL]



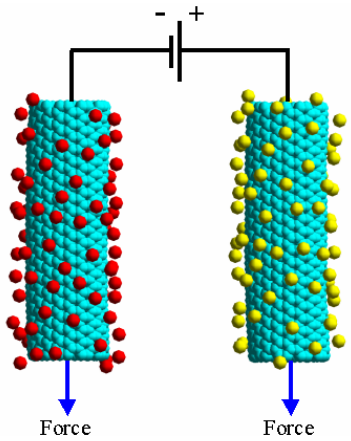
ElectroRheological Fluids (ERF)

[ER Fluids Developments Ltd]



Ionic Gel

[T. Hirai, Shinshu University, Japan]



Carbon-Nanotubes

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

Current EAP

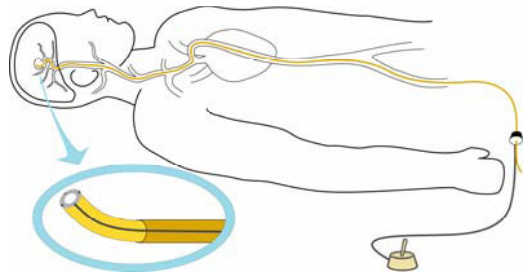
Advantages and disadvantages

Types	Advantages	Disadvantages
Electronic EAP	• Can operate in room conditions for a long time • Rapid response (msec levels) • Can hold strain under dc activation • Induces relatively large actuation forces	• Requires high voltages (~150 MV/m). Recent development allowed for (~20 MV/m) • Requires compromise between strain and stress • 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 • Mostly, producing a monopolar actuation independent of the voltage polarity due to associated electrostriction effect.
Ionic EAP	• Produces large bending displacements • Requires low voltage • Natural bi-directional actuation that depends on the voltage polarity.	• Except for CPs and NTs, 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 electrolysis at >1.23 V requiring • To operate in air requires attention to the electrolyte. • Low electromechanical coupling efficiency.

Medical Applications

Cyborgs potentials for EAP actuators

G. Whiteley, Sheffield Hallam U., UK



Catheter Guide Using IPMC

K. Oguro, ONRI, Japan

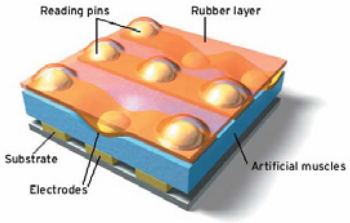
EAP based microanastomosis connector
Micromuscle, Sweden

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

- EAP for Augmentation or Replacement of biological Muscle
- Miniature in-Vivo EAP Robots for Diagnostics and Microsurgery
- Catheter Steering Mechanism
- Tissues Growth Engineering
- Active Braille



Active Braille Display

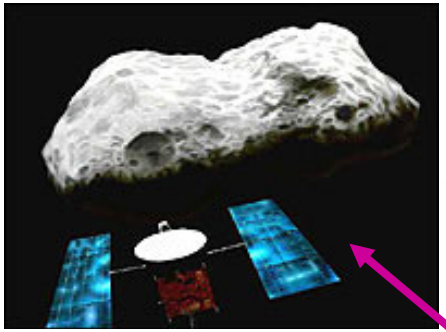
Exploration of planetary applications

Dust wiper

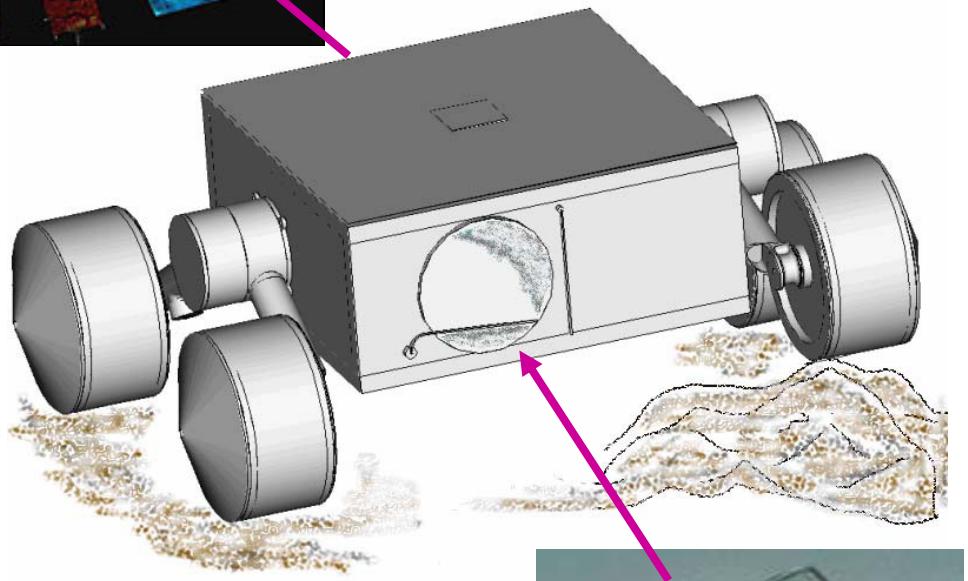
Sample handling robotics

EAP dust wiper

Baselined in the MUSES-CN Nanorover



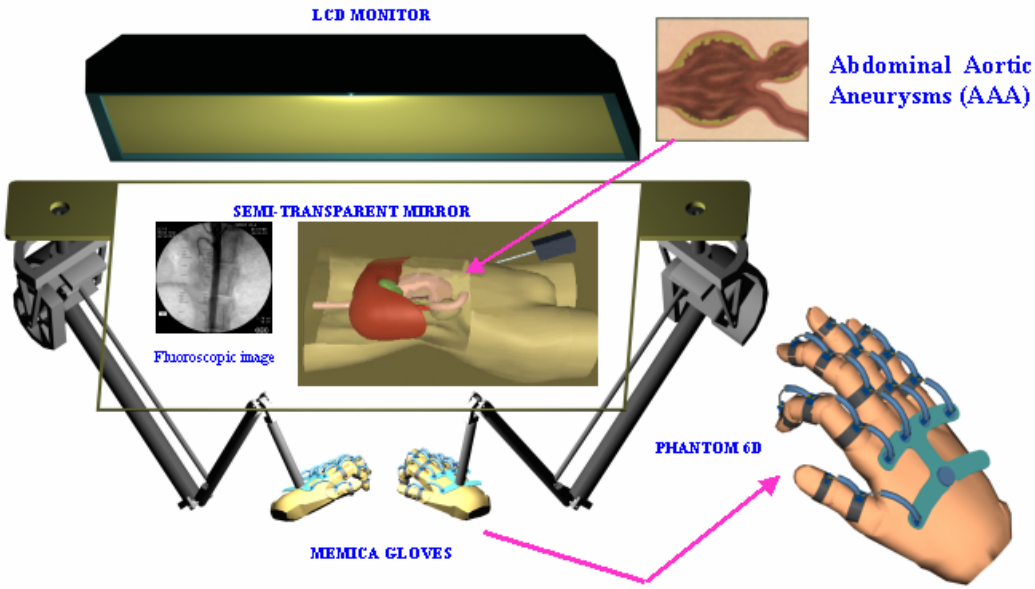
MUSES-CN mission was a joint NASA and NASDA (National Space Development Agency of Japan) mission scheduled for launch in Jan. 2002, from Kagoshima, Japan, to explore the surface of a small near-Earth asteroid. Due to budget constraints, this mission was cancelled in Nov. 2000.

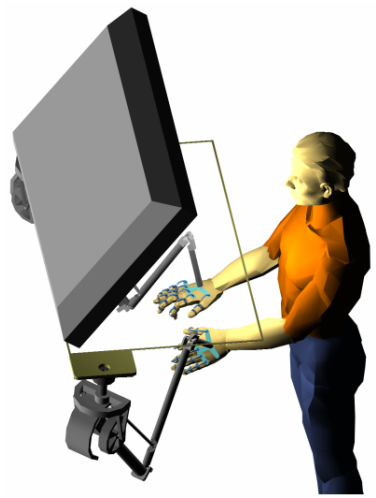


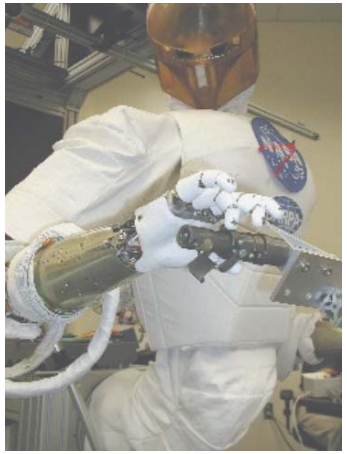
- An IPMC actuated wiper was selected as a baseline for the dust removal from the visual/IR window.
- The technical challenges were beyond the technology readiness requirements

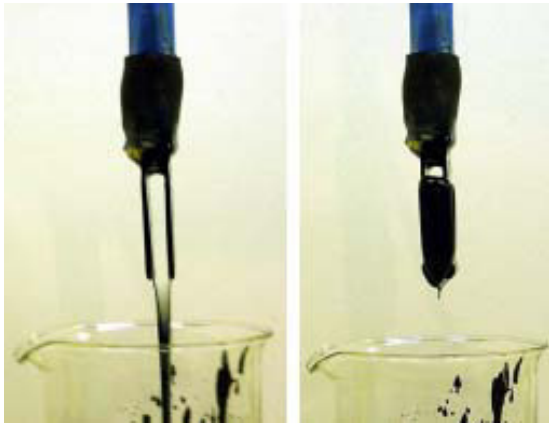
MEMICA*

(MEchanical MIrroring using Controlled stiffness and Actuators)

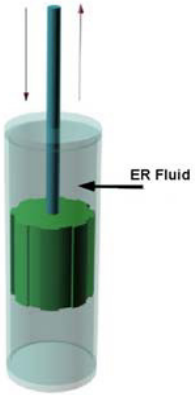


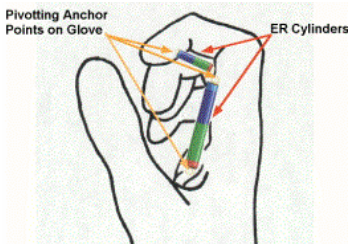






Electro-Rheological Fluid at reference (left) and activated states (right). [Smart Technology Ltd, UK]



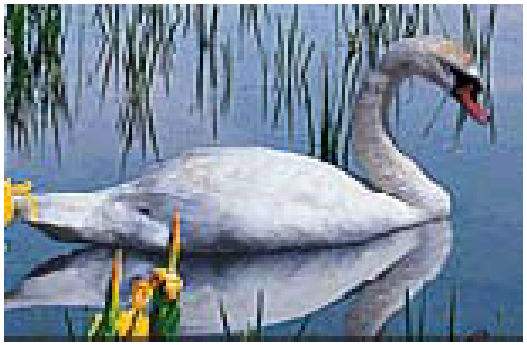


* Joint with C. Mavroidis, formerly Rutgers U.

Models for flexible robots

Multiple locomotion capabilities

Flying, walking, swimming & diving



Hopping, flying, crawling & digging

Coordinated robotics

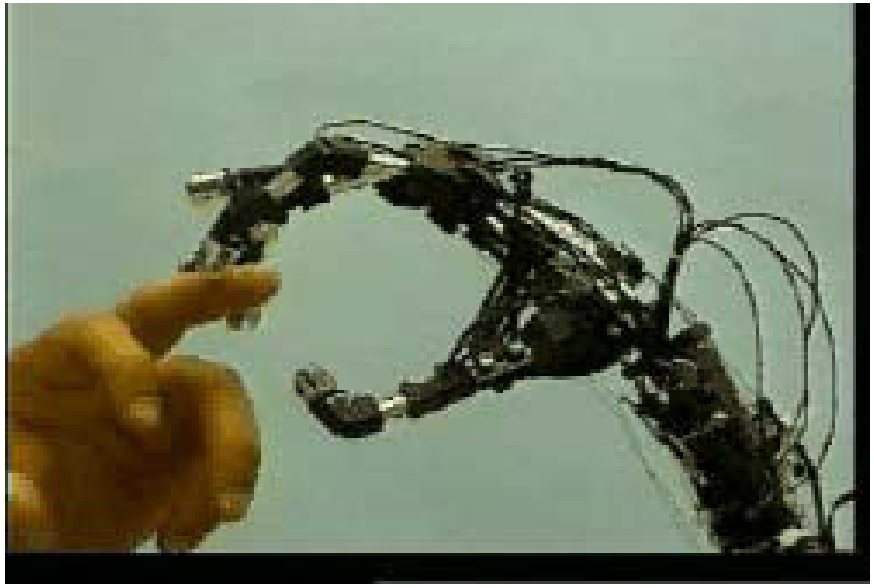
Neural networks & expert systems

Rapid biomimetic prototyping reality

Platforms for EAP Implementation

Android making facial expressions

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

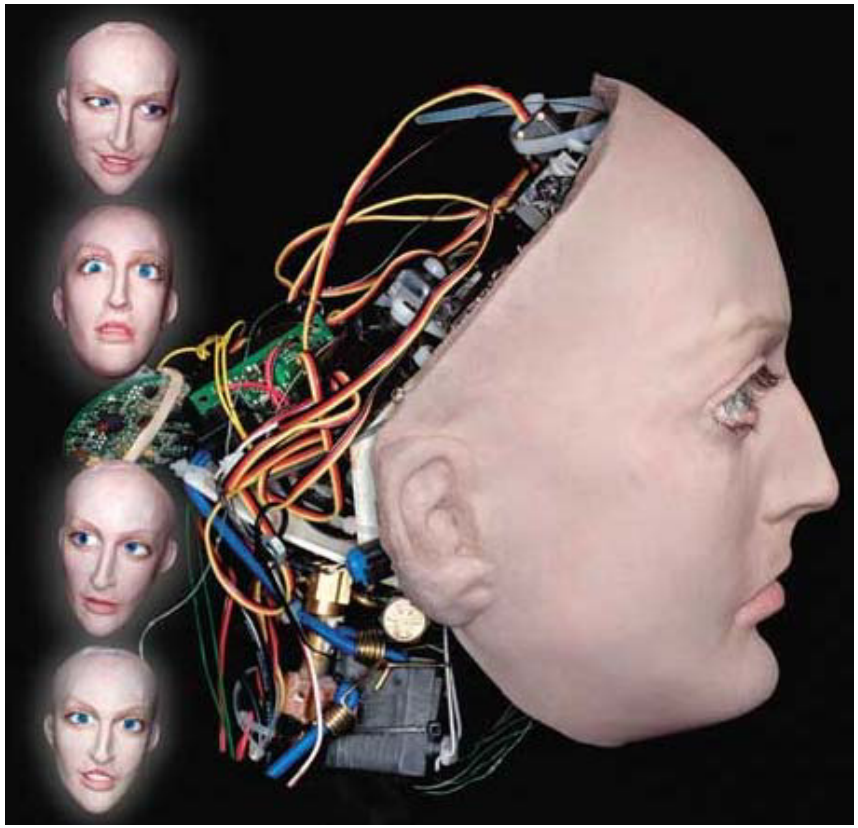


Robotic hand platform for EAP

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

Android heads

Recent android portrait designed by David Hanson - America's science-fiction writers Philip K Dick (created the fiction behind Blade Runner and Minority Report and Total Recall).



Designed by David Hanson, who is a sculptor and engineer [Bar-Cohen, "Electric Flex," IEEE Spectrum, June 2004]

Video can be seen on: http://hansonrobotics.com/movies/sci_ch_NeXtFesT.asf

Full size robot with expressive head

- Humanlike head of Einstein (Hanson Robotics) and Hubo Robot body (KAIST) is the first ever expressive humanlike face on an untethered walking robot.
- This robot was made in celebrations of the 100 years anniversary of the theory of relativity.

Courtesy of David Hanson

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

The grand challenge for EAP as Artificial Muscles

Wrestling match between EAP actuated robotic arm and human

The performance of the human arm as a baseline for the development of EAP actuators

Background

In 1999, a challenge was posed to the worldwide research and engineering community to develop a robotic arm that is actuated by EAP to win an arm wrestling match against a human opponent.

- Initially, the challenge is to win against a human (any human) using a simple shape arm
- The ultimate challenge is to win against the strongest human using the closest resemblance of the human arm.

Objectives

- Promote advances towards making EAP actuators that are superior to human muscles
- Develop the infrastructure including: analytical tools, materials science, electromechanical tools, sensors, control, feedback, rapid response, larger actuation forces, actuator scalability (use of small and large ones), enhanced actuation efficiency, etc.
- Increase the worldwide visibility and recognition of EAP materials
- Attract interest among potential users and sponsors
- Lead to general public awareness – since they will end up being the users/beneficiaries

Current status

- John Brzenk (World Wrestling Champion), John Woolsey (ABC Worldwide wrist-wrestling Champion) and Harold Ryden (California State Champion) attended the 2004 EAP-in-Action Session and were introduced to the attendees to give them an idea about the toughness of this challenge.
- Competition judges were selected and rules were established for the competition.
- The United States ArmSports brought the competition table and provide 2 judges
- The first Armwrestling Match of EAP Robotic Arm against Human (AMERAH) was held on March 7, 2005 as part of the SPIE's EAPAD Conference.
- Three organizations brought their EAP actuated arms to compete
- The 17-year old student, Panna Felsen, won against all three arms

The 1st Armwrestling Contest of human vs. EAP driven robotic arm

The human opponent

- Panna Felsen was a student in the class of 2005 at the La Costa Canyon High School of the San Diego School District and is now a student at Caltech. Panna is a hardworking student who mixes both education priorities and extracurricular activity ranging from recreation sports to robotics.
- Panna took as many as six AP courses in a school year—and earned all A's in course work that included advanced calculus and physics. In her junior year, she founded an engineering club at her school for which her robotics knowledge helped the team win KISS Institute's National Research and Design Challenge. She also taught the members IC programming and led the design team that built and programmed autonomous robots for which her Botball team earned second place at Southern California Regionals. During the summer, 2004, she was selected as a NASA Sharp Apprentice to do paid research at the University of Michigan. Ultimately, she plans to enter the engineering field.
- She lived in Encinitas, California, which was located north of San Diego, where she enjoyed shooting hoops at the YMCA and occasional walked to the beach from her home. What was once training ground during her eight-year competitive swimming regimen, the beach became a place where she went only for recreation to ride her boogie board and to build extreme sand castles—when she allowed herself the free time. Panna's interests began to change from athletics to academics when she was introduced to Botball robotics in middle school.
- Currently, Panna served as the only student member of the San Diego Science Alliance Robotics Steering Committee, the group that first introduced her to robotics. She was also organizer of her school's participation in Science Olympiad, and on weekends, she worked as a ballroom dance junior instructor for the San Dieguito Cotillion.

Panna Felsen - Represented humans in the 1st armwrestling competition with EAP driven robotic arms

The Contest Rules

The following rules are intended to assure the safety of the human competitor and the fairness/sportsmanship of the competition. These rules were defined for the robot and human competitors and are envisioned to be modified as advancements are made in EAP.

1. The safety of the human wrestler is the #1 priority of this competition. Safety measures should be taken to assure that the human will not be subjected at any time to any hazardous conditions.
   - To protect the human wrestler from harm, a termination switch should be provided with quick access to allow terminating the competition in case of unforeseen condition that may lead to hazard.
2. The robotic arm has to be actuated by an EAP material and the actuators should be approved by the organization committee prior to the participation in the competition.
3. Access to the drive actuators should be made available to allow direct viewing and confirmation of the drive mechanism prior to the beginning to the match.
4. As realistic as possible, the robot arm should emulate the wrestling action of a human arm.
5. As much as possible, the structural elements of the robot arm should be made of polymer base materials.
6. The shape and dimensions of the robotic arm should match an arm of an average adult human.
7. The robotic arm should have a mechanism that is reversible, namely, it should be possible to rotate the arm both left and right in order to equally assure the ability to win or lose.
8. The robot should not perform any irritating acts (heating, vibration, irritating noise, blinding lights, etc.) or any acts that are beyond human capability

The 1st Armwrestling Contest

March 7, 2005

Environmental Robots Inc. (ERI), Albuquerque, NM, used dielectric elastomer and of ionic polymer metal composites (IPMC) strips – this arm lasted 26-sec.

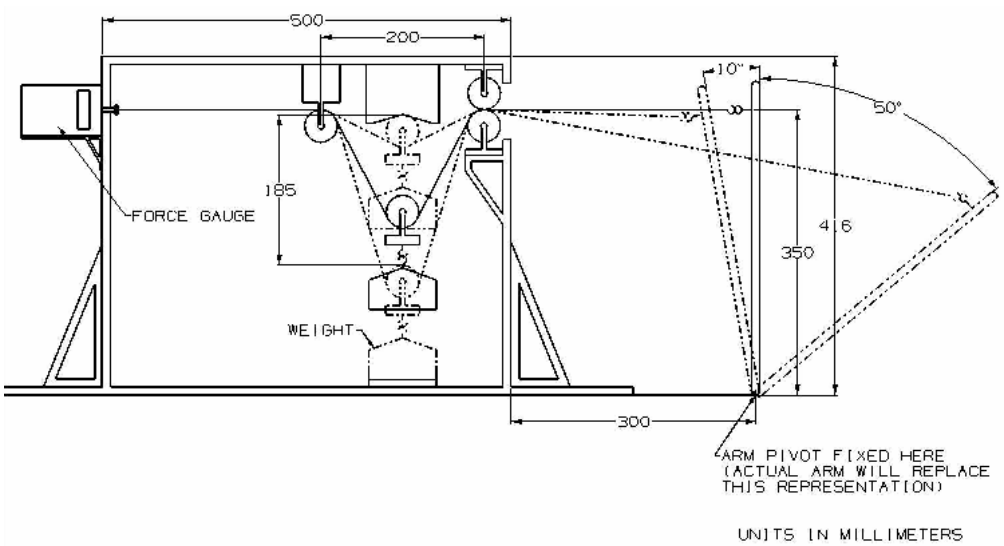
Students from VT used PAN gel fibers and an electrochemical cell – this arm lasted 3-sec.

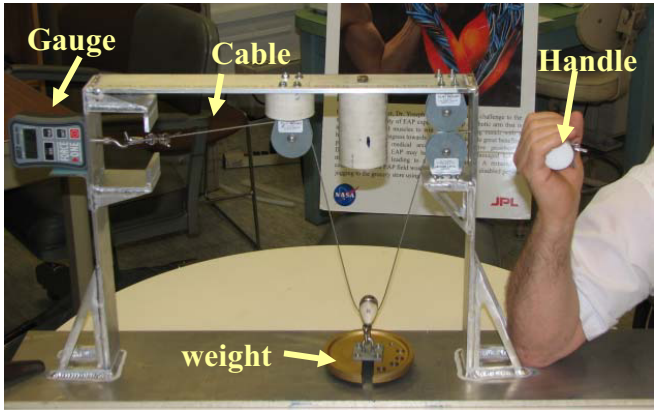
EMPA, Dubendorf, Switzerland used dielectric elastomer in 4 groups of multi-layered scrolled actuators– this arm lasted 4-sec.

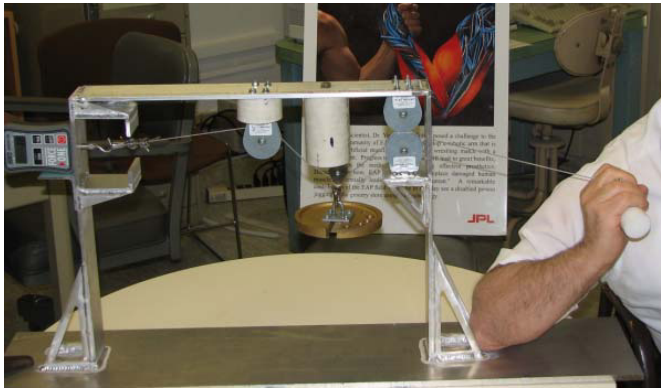
Video of the three wrestling matches

The 2nd armwrestling contest (2006)

The competing arms were measured for strength and speed using a gauging fixture







Acknowledgement: The test fixture was designed and constructed jointly with Qibing Pie and his students from UCLA

The 2nd Armwrestling Contest (2006)

Strongest arm

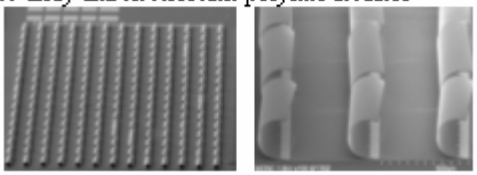
Human as baseline

Fastest arm

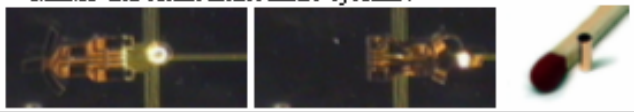
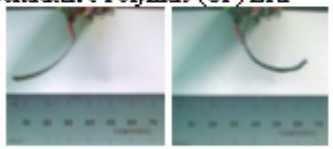
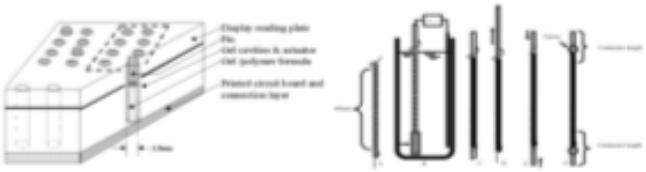
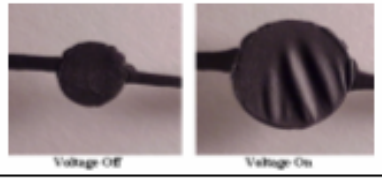
The results of the 2nd Armwrestling Contest

	Lifted height	Force (lbf)	Speed (in/sec)	Notes
Panna Felsen	9.78"	21.8	>9.78	**BASELINE**
VT - Eng. Sci. & Mech. (lead Cotton/ Josh)	~8.78" (started from bottom level)	0.2	~0.037	**Strongest**
ERI (Shahinpoor)	~3.28" (started from 6" height)	0.2	~0.045	**Fastest**
VT - Mech. Eng. (lead Barbar/Jaime)	Upon activation actuators failure occurred			

EAP material and product manufacturers

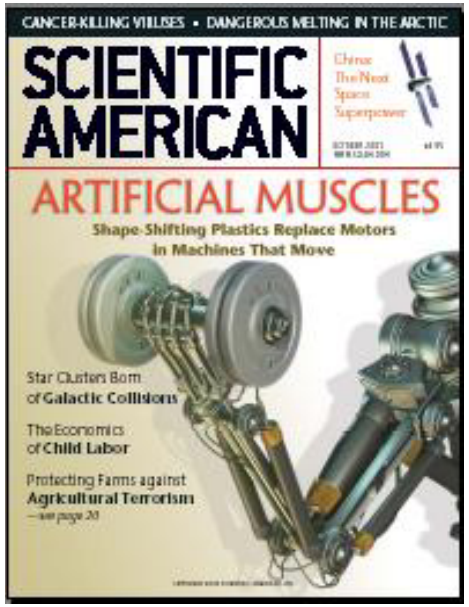
Company Name, Contact person, E-mail, Website	EAP materials/processes/products
Artificial Muscle, Inc. (AMI)* 333 Ravenswood Ave., Menlo Park, CA 94025 Artificial Muscle Inc Alex N. Beavers, Jr., Ph.D. Chief Executive Officer; alex@artificialmuscle.com www.artificialmuscle.com *Founded by SRI International	▪ Design and manufacture EAP based solid state actuators, sensors, and generator components for automotive, industrial machinery and automation, electronics, consumer goods, medical, and aerospace. ▪ EAP devices including valve controllers, pumps, electric servo motor replacement, force and pressure sensors, acoustic speakers, and linear position actuators.
EAMEX Corporation 5-16-608 Uhocyou, Ikeda city, Osaka, Japan Shingo Sewa or Kazuo Onishi; web@eamex.co.jp; http://www.eamex.co.jp/index_e.html	• Conductive polymer EAP and IPMC actuators • 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 EAP based hand
Environmental Robots Incorporated 909 Virginia, NE., Suite 205, Albuquerque, New Mexico 87108, USA Mohsen Shahinpoor or Massoud Ahghar; shah@environmental-robots.com or mahghar@environmental-robots.com; www.environmental-robots.com	▪ IPMC-based and ionic polymer actuators, transducers, and sensors ▪ IPMC and conductive polymer EAP for biomedical engineering and medical applications ▪ Kits of bending and contractile EAP, ionic polymeric fiber bundles, conductive polymers and chemically activated polymers IPMC
MCNC Research and Development Institute Scott Goodwin, goodwin@mcnc.org, http://www.mcnc.org/rdi/	Dielectric EAP device development and prototyping of ▪ "Artificial Eyelid" polymer flexible film ▪ Electrostatic MEMS actuator ▪ Integrated force array and electrostatic polymer actuator Artificial Eyelid 

EAP material and product manufacturers

Micromuscle AB Westmansgatan 29, 582 16 Linköping, Sweden, Edwin Jager, CTO, edwin.jager@micromuscle.com; Gert Kindgren, CEO, gert.kindgren@micromuscle.com; www.micromuscle.com	▪ EAP Products include materials and devices ranging from cellular levels for lab-on-a-chip to implantation in the human body. ▪ Conductive polymers EAP actuators ranging in size from micrometers to several centimeters. ▪ Components and devices for medical devices, vascular surgery, MEMS and biomedicine micro-systems. 
Molecular Mechanisms LLC Customer Support, sales@molecularmechanisms.com, www.molecularmechanisms.com	▪ Development of EAP based mechanisms ▪ Polypyrrole (PPy) tapes for Conductive Polymers (CP) EAP  Bilayer CP EAP activated in air
Nano Sonic, Inc. 1485 S. Main Street Blacksburg, VA 24060 Richard O. Claus, President; info@nanosonic.com; http://www.nanosonic.com	▪ Low modulus sensors for strain, vibration and fluid flow ▪ Free-standing conductive and reflective elastomeric membranes ▪ Flexible electroding for EAP actuators using modified self-assembly (demonstrated for dielectric EAP) Stretchable electroding material
Quantum Technology Pty. Ltd. 5 South Street, Rydalmere, N.S.W. 2126, Australia Tim Connell tconnell@quantech.com.au http://www.quantech.com.au/	▪ Development of EAP actuators for Braille Cells as an aid to visually impaired and blind. 
SRI International* 333 Ravenswood Avenue, Menlo Park, CA 94025 Philip von Guggenberg, Director of Business Development, pvong@sri.com, www.sri.com/artificialmuscle * In 2008, AMI was found to commercialize the EAP technology	▪ Dielectric EAP actuators ▪ Devices and mechanisms that are driven by dielectric EAP ▪ R&D contracts to explore and extend the application of EAP technologies to scientific, industrial, and military environments from nano to mega scale devices.  Dielectric EAP

Recent Progress

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



Cover page of the Oct. 2003 issue

The first arm wrestling arm competition was held on March 7, 2005 and three different arms competed against a 17-year old student. The student won against all three where the strongest arm was the one made by Environmental Robots Incorporated (ERI), NM and it lasted 26-seconds.

Current EAP actuators scale

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

EMPA, Switzerland

Robotic Fish

The 1st commercial EAP-actuated product (2002)

Developed by Kazuo Onishi and Shingo Sewa, EAMEX Corp

Summary

- Artificial technologies (AI, AM, and others) are increasingly becoming practical tools for making biologically inspired devices and instruments with enormous potential for space applications.
- Polymer materials are used to produce figures that resemble human and animals. These materials are widely employed by the movie industry for making acting figures and by the orthopedic industry to construct cyborg components.
- Electroactive polymers (EAP) are human made actuators that are the closest to mimic biological muscles.
- Technology was advanced to the level that biologically inspired robots are taking increasing roles in the world around us and making science fiction ideas a closer engineering reality.

- There are still many challenges ahead that are critical to making such possibilities practical.
  - The annual armwrestling contest is providing an exciting measure of how well advances in EAP are implemented to address the field challenges.
- There is a need to document natures' inventions in an engineering form to possibly inspire new capabilities.