Biologically-Inspired Intelligent Robots
BIOMIMETIC ACTUATION MATERIALS

Yoseph Bar-Cohen, JPL/Caltech, Pasadena, CA
818-354-2610, yosi@jpl.nasa.gov
http://ndeaajpl.nasa.gov/

AAAS Annual Meeting
Denver, CO, February 16, 2003
Wishful thinking
List of content

- Symposium Overview
- Artificial Muscles
- Infrastructure
- Planetary Applications
- Challenges
- Outlook
Nature as a model for robotics engineering

Tumbleweed

Helicopter (Tipuana tipu)

Glider (Alsomitra macrocarpa)

Aerodynamic dispersion of seeds

(Courtesy of Wayne's Word)

Ref: http://wayne'sword.palomar.edu/plfeb99.htm#helicopters

Octopus adaptive shape, texture and camouflage

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

Courtesy of William M. Kier, of North Carolina

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

Quadruped Walking Machine to Climb Slopes at the Univ. of Nagoya, Japan

Six legged robot at the AI Lab, Univ. of Michigan

Fully Contained 3D Bipedal Walking Dinosaur Robot at MIT

Snake-like – by Mark Tilden
Lemur - 6-legged robots at JPL

Staged Simulation
Smart Toys

Sony’s SDR3

Honda’s Asimo
Ref: http://world.honda.com/robot/movies/

AIBO - Sony 2nd Generation ERS-210

I-Cybie
Ref.: http://www.i-cybie.com
Entertainment industry

Jim Henson’s Creature Shop, animatronic creature with skin

Walt Disney Imagineering “Haunted Mansion© Disney” at Disneyland

Smiling Robot of Hidetoshi Akasaw.
Robot that responds to human expressions
Cynthia Breazeal and her robot Donna
Elements of an EAP actuated robots

Communication

Intelligent control
- Navigation
- Collision avoidance
- Autonomous performance

Sensing
- EAP actuation sensors
- Imaging
- Other sensors as needed

EAP Actuator

Power

Propulsion/Mobility/Locomotion Functions
- Swimming and/or diving
- Walking
- Hopping and/or flying
- Microswitching and positioning
**Background**

- Most conventional mechanisms are driven by actuators requiring gears, bearings, and other complex components.

- Emulating biological muscles can enable various novel manipulation capabilities that are impossible today.

- Electroactive polymers (EAP) are emerging with capability that can mimic muscles to actuate biologically inspired mechanisms.

- EAP are resilient, fracture tolerant, noiseless actuators that can be made miniature, low mass, inexpensive and consume low power.

- EAP can potentially be used to construct 3-D systems, such as robotics, which can be imagined today as science fiction.
Comparison between EAP and widely used transducing actuators

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

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

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

Multiple locomotion capabilities

Flying, walking, swimming & diving

Hopping, flying, crawling & digging

Models for EAP Actuated Flexible Robots

Coordinated robotics

Neural networks & expert systems

Soft landing
Insects were used by various researchers (e.g., University of Tokyo, Japan) as locomotives to carry backpack of wireless electronics.

EAP offers the potential of making insect-like robot to replace the “real thing”.

Reference: http://www.leopard.t.u-tokyo.ac.jp/
Non-Electro Active Polymers (NEAP)

- Conductive and Photonic Polymers
- Smart Structures and Materials
- Deformable Polymers
  - Chemically Activated
  - Shape Memory Polymers
  - Inflatable Structures
  - Light Activated Polymers
  - Magnetically Activated Polymers
Non-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)
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.
Artificial Muscles

EAP

Yoseph Bar-Cohen, Ph.D.
Jet Propulsion Laboratory
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)
Electronic EAP
ELECTRIC FIELD OR COULOMB FORCES DRIVEN ACTUATORS

Paper EAP
[J. Kim, Inha University, Korea]

Ferroelectric
[Q. Zhang, Penn State U.]

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]

Ionic Gel
[T. Hirai, Shinshu University, Japan]

ElectroRheological Fluids (ERF)
[ER Fluids Developments Ltd]

Carbon-Nanotubes
[R. Baughman et al, Honeywell, et al]
## Current EAP
### Advantages and disadvantages

<table>
<thead>
<tr>
<th>EAP type</th>
<th>Advantages</th>
<th>Disadvantages</th>
</tr>
</thead>
</table>
| 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 (~150V/µm)  
- 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 |
Applications of EAP to potential planetary tasks
Considered planetary applications

**Dust wiper**
Bending EAP is used as a surface wiper

**Sample handling robotics**
Extending EAP lowers a robotic arm, while bending EAP fingers operate as a gripper
EAP Dust Wiper
for the MUSES-CN Nanorover

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

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

Actuated by 1-3 volts

Biased with 1-2KV for dust repulsion

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

* Made by Energy Science Laboratories, Inc., San Diego, California
Challenges and solutions to the application of IPMC as bending actuators

<table>
<thead>
<tr>
<th>Challenge</th>
<th>Potential Solution</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fluorinate base - difficult to bond</td>
<td>Etching the surface makes it amenable to bonding</td>
</tr>
<tr>
<td>Extremely sensitive to dehydration</td>
<td>Apply protective coating over the etched IPMC</td>
</tr>
<tr>
<td>Off-axis bending actuation</td>
<td>Constrain the free end and use a high ratio of length/width</td>
</tr>
<tr>
<td>Operate at low temperatures</td>
<td>IPMC was demonstrated to respond at -100(^\circ)C in vacuum</td>
</tr>
<tr>
<td>Remove submicron dust</td>
<td>Use effective wiper-blade design and high bias voltage</td>
</tr>
<tr>
<td>Reverse bending drift under DC voltage</td>
<td>Limit the operation to cyclic activation to minimize this effect, and use cations such as Li(^+) rather than Na(^+).</td>
</tr>
<tr>
<td>Protective coating is permeable</td>
<td>Develop alternative coating, possibly using multiple layers</td>
</tr>
<tr>
<td>Electrolysis occurs at &gt;1.23-V</td>
<td>Use efficient IPMC that requires low actuation voltage</td>
</tr>
<tr>
<td>Residual deformation particularly after intermittent activation</td>
<td>It occurs mostly after DC or pulse activation and it remains a challenge</td>
</tr>
<tr>
<td>Difficulties to assure material reproducibility</td>
<td>Still a challenge. May be overcome using mass production and protective coating.</td>
</tr>
<tr>
<td>Degradation with time due to loss of ions to the host liquid</td>
<td>Requires electrolyte with enriched cation content of the same species as in the IPMC</td>
</tr>
</tbody>
</table>
MEMICA
(MEchanical Mimicking using Controlled stiffness and Actuators)

Abdominal Aortic Aneurysms (AAA)

Electro-Rheological Fluid at reference (left) and activated states (right). [Smart Technology Ltd, UK]
MEMICA-based exoskeleton for countermeasure of astronauts bones and muscles loss in microgravity. It has potential application as:

- Assist patient rehabilitation
- Enhance human mobility
Elements of the EAP Infrastructure
EAP infrastructure

EAP material pool
- Ionic Gel
- IPMC
- Conductive polymers
- Nanotubes
- Dielectric EAP
- Ferroelectric
- Graft elastomer

EAP mechanism understanding and enhancement
- Nonlinear electromechanical modeling
- Material properties characterization
- Computational chemistry
- New material synthesis

EAP processing
- Material fabrication techniques
- Shaping (fibers, films, etc.)
- Microlayering (ISAM & inkjet printing)
- Support processes and integration (electroding, protective coating, bonding, etc.)
- Miniaturization techniques

Tools/support elements
- Sensors
- Actuators
- MEMS

Devices/Applications
- Miniature Robotics
  - Insect-like robots
  - End effectors
  - Manipulators
  - Miniature locomotives
- General applications and devices
  - Medical devices
  - Shape control
  - Muscle-like actuators
  - Active weaving and haptics
Computational chemistry may lead to material design tools using comprehensive modeling to methodically synthesize effective new EAPs.
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.

**Activation signal**

Frequency - 0.05 Hz

**IPMC mechanical response**

**Current**

[mA]

**Voltage**

[V]

**Time**

[sec]
Applications
Underway or under consideration

- **Mechanisms**
  - Lenses with controlled configuration
  - Mechanical Lock
  - Noise reduction
  - Flight control surfaces/Jet flow control
  - Anti G-Suit

- **Robotics, Toys and Animatronics**
  - Biologically-inspired Robots
  - Toys and Animatronics

- **Human-Machine Interfaces**
  - Haptic interfaces
  - Tactile interfaces
  - Orientation indicator
  - Smart flight/diving Suits
  - Artificial Nose
  - Braille display (for Blind Persons)

- **Planetary Applications**
  - Sensor cleaner/wiper
  - Shape control of gossamer structures

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

- **Liquid and Gases Flow Control**

- **Controlled Weaving**
  - Garment and Clothing

- **MEMS**

- **EM Polymer Sensors & Transducers**
Interfacing human and machine to complement or substitute our senses would enable important medical applications.

Researchers at Duke U. connected electrodes to a brain of a 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
(S. Tadokoro, Kobe U., Japan)

Active Braille Display
Platforms for EAP Implementation

Android making facial expressions
[Sculptured by D. Hanson, U. of Texas, Dallas, and instrumented by jointly with G. Pioggia, University of Pisa, Italy]

Robotic hand platform for EAP
[G. Whiteley, Sheffield Hallam U., UK]
Related recent and upcoming books

Other References

Proceedings

SPIE


MRS


Websites


WW-EAP Newsletter

SUMMARY

- Artificial technologies (AI, AM, and others) for making biologically inspired devices and instruments are increasingly being commercialized.

- Materials that resemble human and animals are widely used by movie industry and animatronics have advanced to become powerful tools.

- Electroactive polymers are human made actuators that are the closest to resemble biological muscle potentially enabling unique robotic capabilities.

- Technology has advanced to the level that biologically inspired robots are taking increasing role making science fiction ideas closer to an engineering reality.
The grand challenge for EAP as Artificial Muscles
Nothing can stop automation