Intelligent materials for extreme environments

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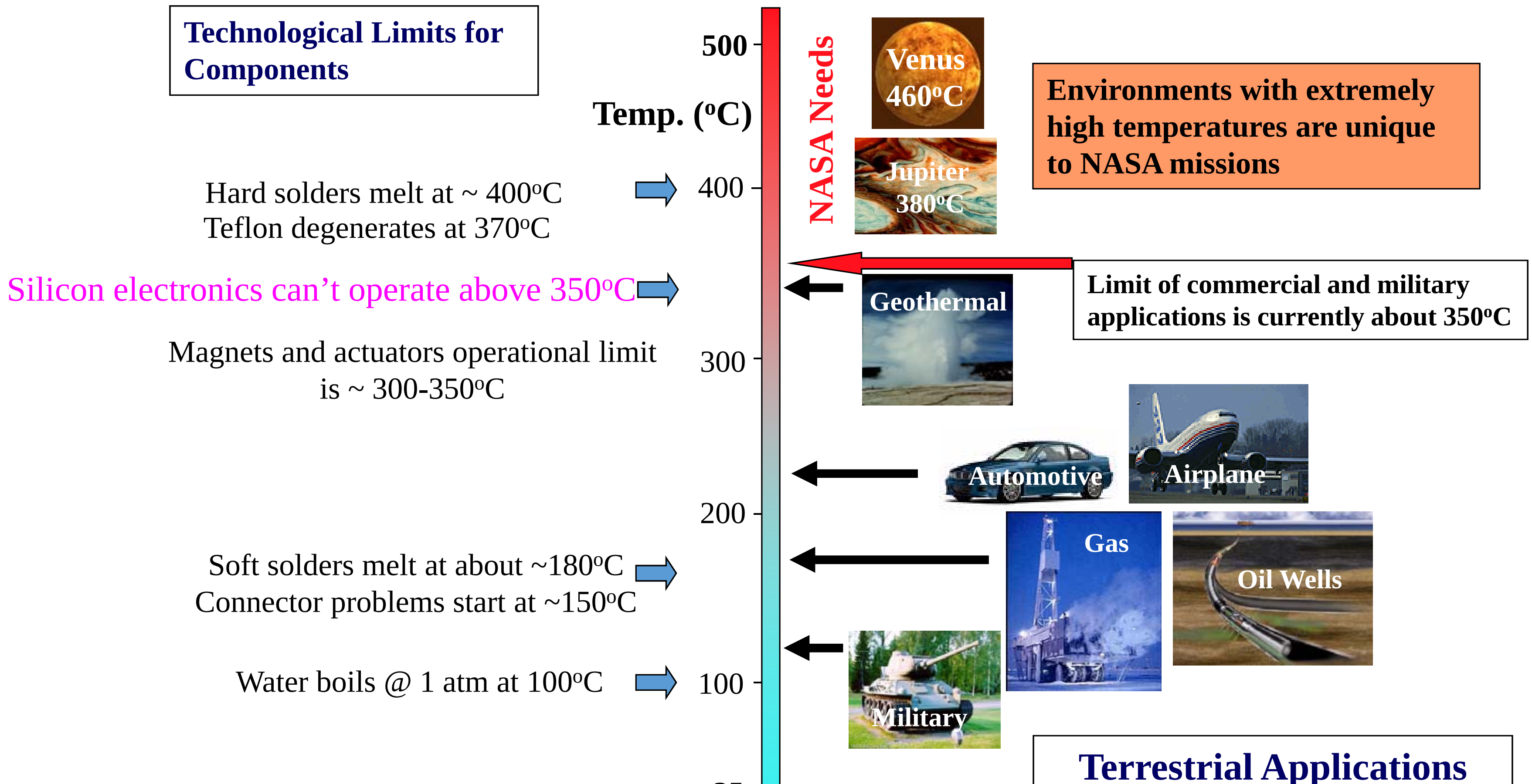
"Adaptive Multi-Functional Space Structures for Micro-Climate Control Part II"
Workshop at Caltech
Sponsored by the Keck Institute for Space Studies

Applications of intelligent materials

- Mobility
- Actuation
- Manipulation
- Transport
- Sample handling (gripping, crashing, etc.)
- Deployment and pointing
- Folding and unfolding
- Digging, penetration, tunneling
- Sample acquisition
- Pumping
- Infrastructure construction

HT limits of conventional technologies

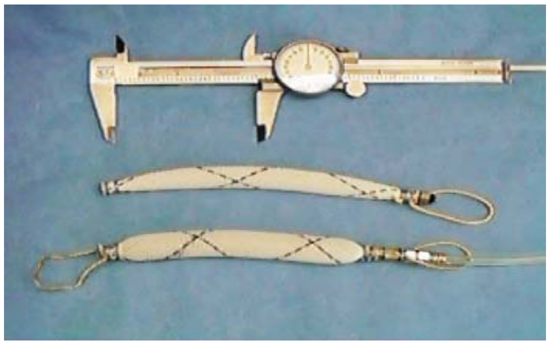


Ref: Based on Kolawa, SSETAG, 2002

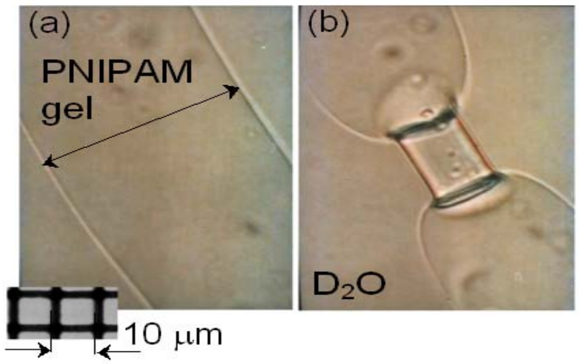
HT Intelligent materials

- **Piezoelectrics**: This effect takes place in crystalline materials with no inversion symmetry and it is a linear electromechanical interaction between the mechanical and the electrical states.
- **Electrostriction**: This effect involves deformation of dielectrics in an electric field and it is proportional to the square of electric field strength and it is resulted from the induced dielectric polarization.
- **Magnetostrictive materials**: These are materials that convert electromagnetic into mechanical energy. Examples of such materials include nickel and some of its alloys.
- **Photostriction**: Generation of strain by irradiation of light and it can be observed in ceramics. One such material is the PLZT (made of Lead, Lanthanum, Zirconium, and Titanium).
- **Electroactive Polymers**: A family of materials that mechanically respond to electrical stimulation
- **Shape Memory Materials**: Materials that display two distinct crystal structures or phases, which is a function of the temperature and internal stresses. They include Shape memory Alloys and Polymers
- **Electrorheological fluids (ERF)**: These fluids are suspensions of extremely fine non-conducting particles ($\leq$50 µm diameter) in an electrically insulating fluid. In response to an electric field, their apparent viscosity changes reversibly by $\leq$5 orders of magnitude and in mSec.
- **Magnetorheological fluid (MR fluid)** - Similar to ERF but using magnetic particles.

None electro-mechanically activated polymers

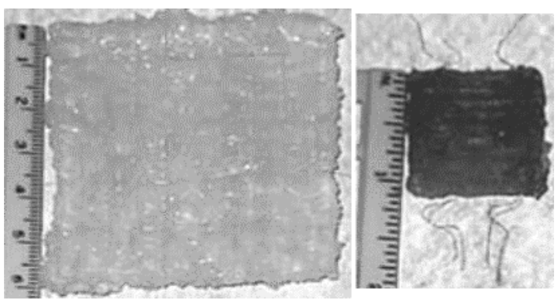


McKibben Artificial Muscles
Air Pressure activation (B. Hannaford, U. of Washington)

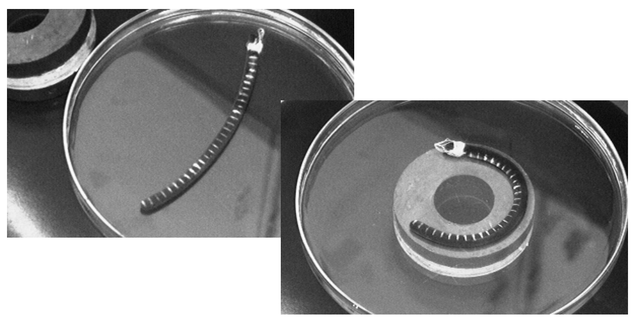


Laser Illuminated Polymer
Light activation (H. Misawa, Japan)

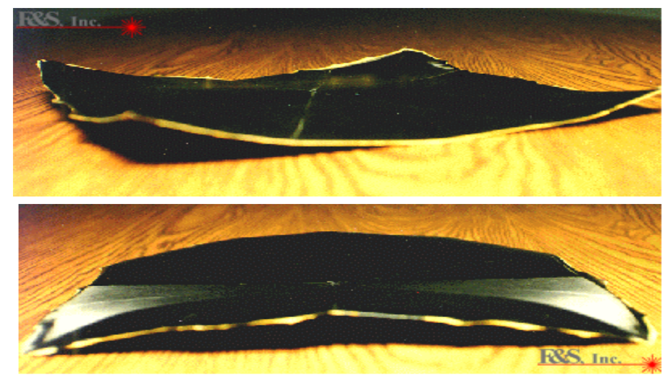
Shape Memory Polymers
Heat/pressure activation (W. Sokolowski, JPL)



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



Ferrogel
Magnetic Activation (M. Zrinyi, Hungary)



Smart Structures
Polymers with bi-stable shapes
(S. Poland, Luna Innovations, VA)

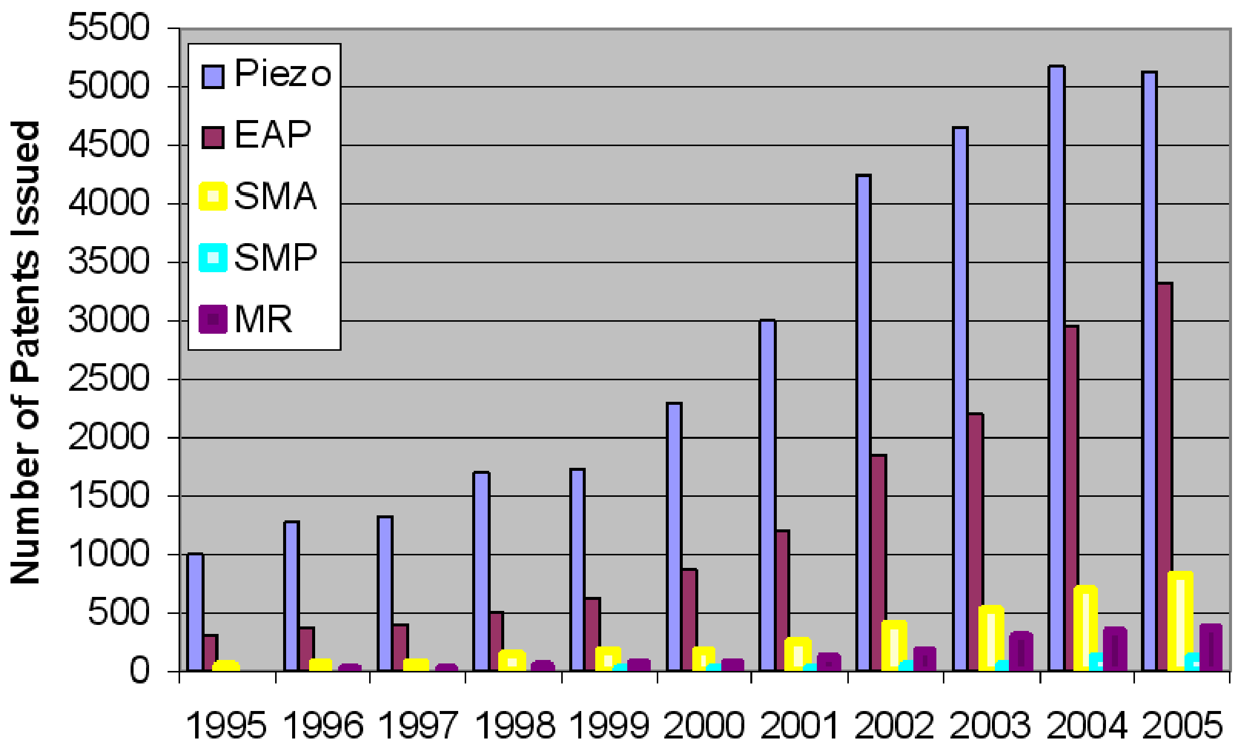
Comparison between three transducing actuators

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

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

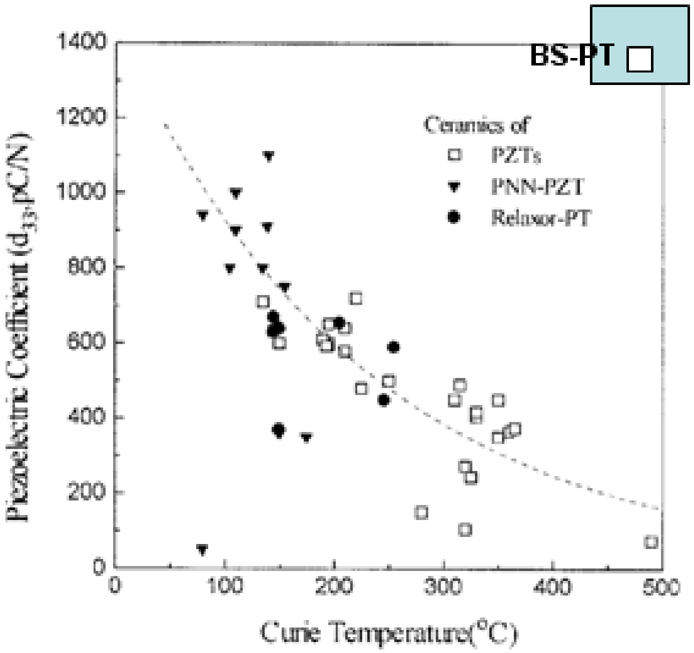
Automotive Industry Trends

1995- 2005 Patents

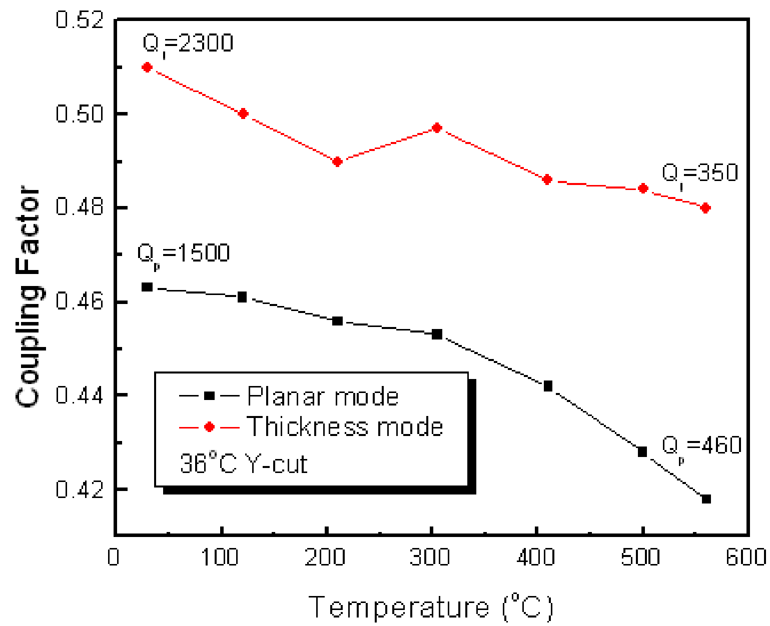


Courtesy: Nancy L. Johnson, General Motors R & D, Warren, MI

HT piezoelectric materials



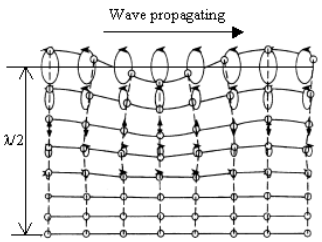
Piezoelectric coefficient as a function of temperature for several crystal materials

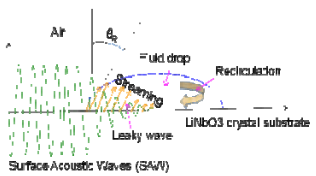


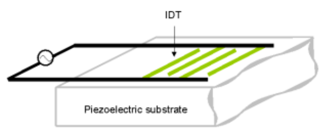
The coupling factor as a function of temperature for LiNbO3 (36° Y-cut) crystals

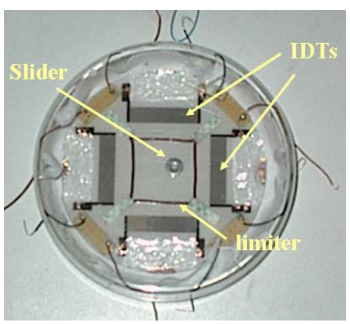
Ref.: Y. Bar-Cohen, X. Bao, J. Scott, S. Sherrit, S. Widholm, M. Badescu T Shrout and B. Jones, "Drilling at high temperatures using ultrasonic/sonic actuated mechanism," ASCE's Earth and Space 2010 conference, Honolulu, HI on March 14-17, 2010.

Surface Acoustic Wave (SAW) motors



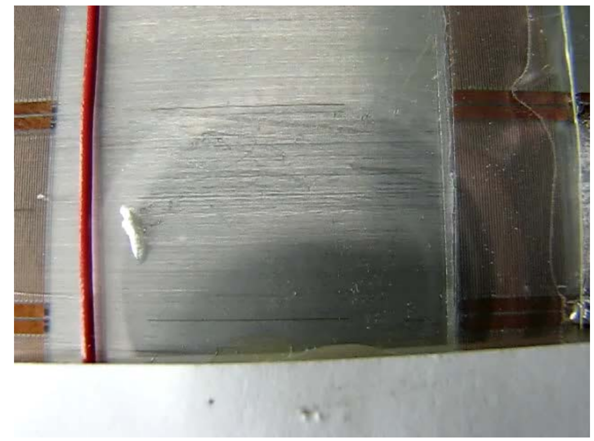


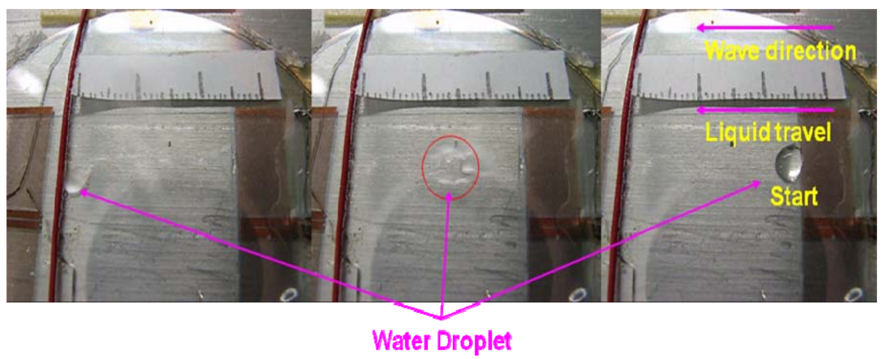




2D SAW motor

Snapshots from the travel of WCA 12 powder with 50% 7–8.5 μm particles.

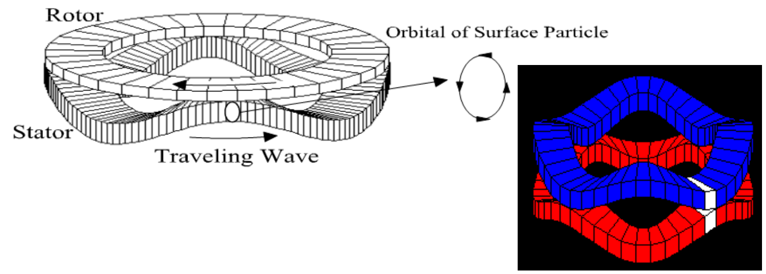


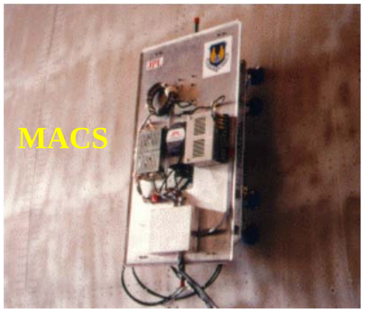


Snapshots from the travel of water droplet (the travel direction here is from right to left).

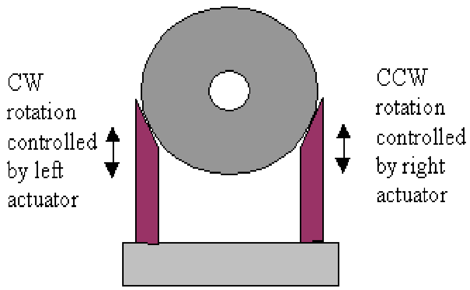
ULTRASONIC MOTORS (USM) ADVANTAGES

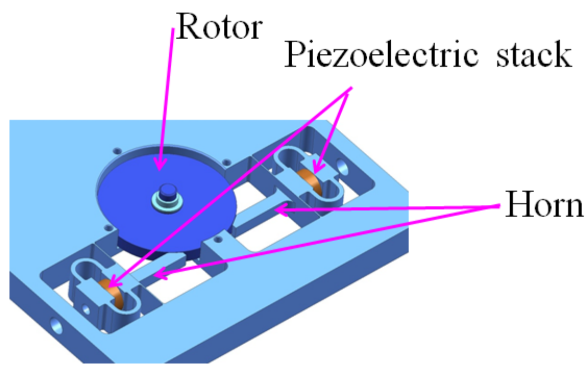
- Low speed and direct drive
- Order of magnitude higher torque density than electromagnetic motors
- Unique configurations: Pancake as well as annular shape for electronic packaging
- Lower cost, easy to miniaturize and to mass produce
- Inherently backdrivable (self braking)
- Not affected by magnetic field or radiation

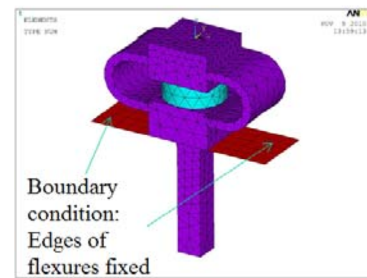


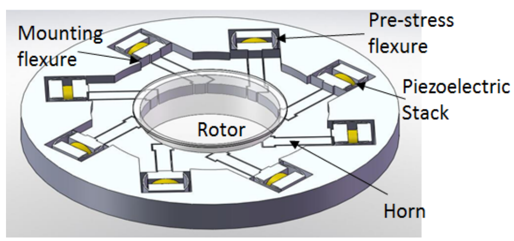


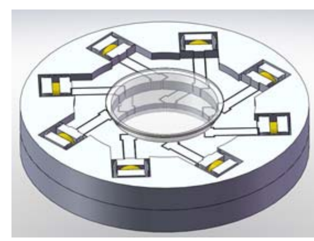
Barth Motors

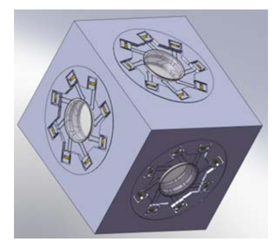




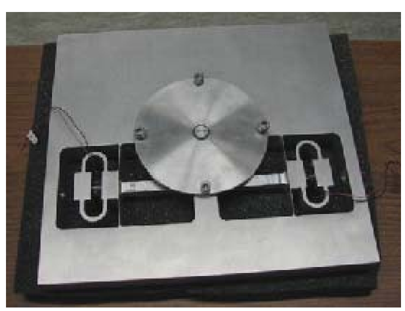


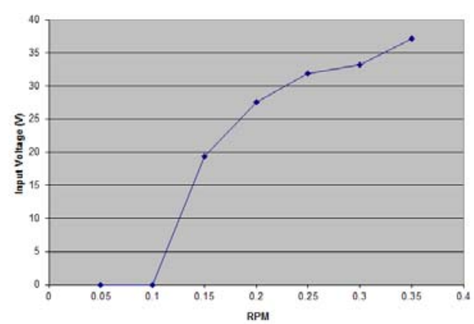


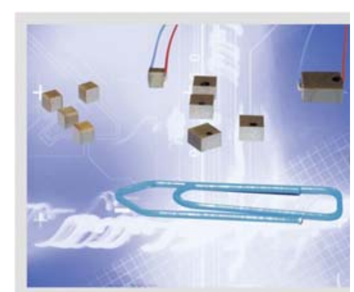




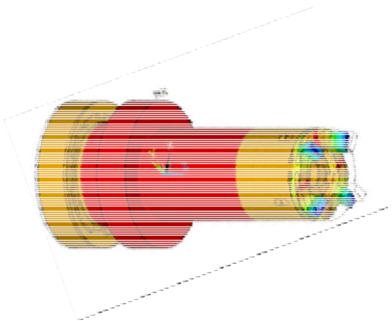
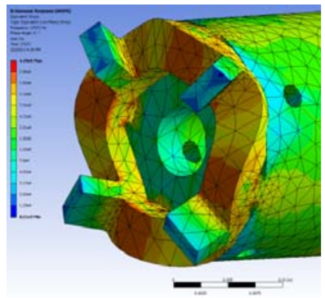
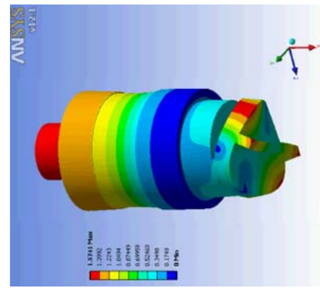
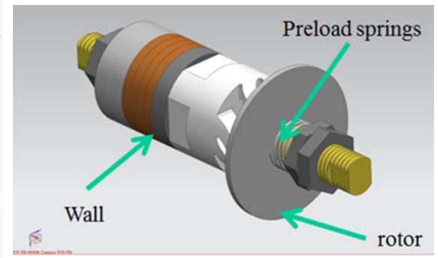
Unidirectional, bidirectional and 3D motor designs

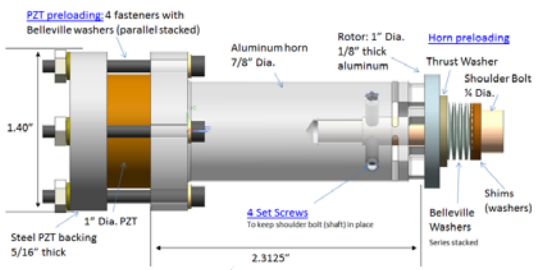




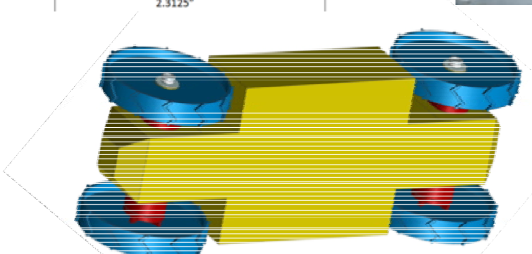
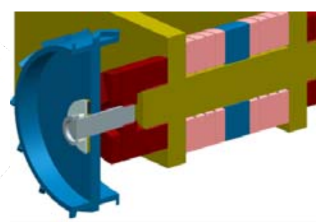
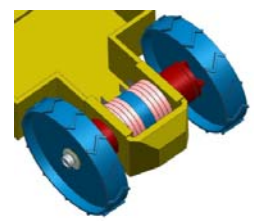


Piezo-Ratcheting Actuator





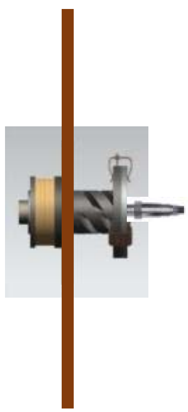




REF:

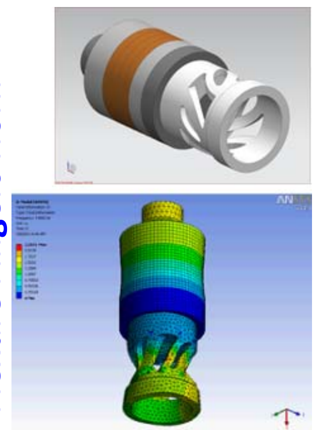
- S. Sherrit, Y. Bar-Cohen, and X. Bao, “Acoustic Mechanical Feed-throughs (AMF): for producing work across a structure,” NTR Docket No. 48422 (2011).
- Y. Bar-Cohen, S. Sherrit, and M. Badescu, “Miniature multi-functional self-braking vehicle actuated by piezoelectric stacks thru the fuselage walls”, NTR Docket No. 49101 (2013).

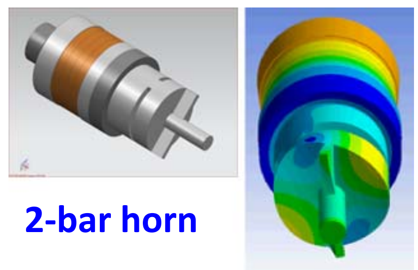
Compact Rotary-Hammering Sampler

- The Acoustic Mechanical Feed-throughs (AMF) capability was demonstrated to consistently and efficiently induce rotation through a wall using mode conversion of vibrations generated by piezoelectric stack
  - Analytical modeled, simulated and optimized design of various configurations of acoustic mechanical feed-throughs that are driven by piezoelectric stacks.
  - The designs that were developed and tested were the Kumada, 4-bar horn, and flexure finger.
- The three designed and fabricated configurations have been successfully tested. The 2-bar horn showed rotation of over 800 RPM and the 4-bar horn design showed a rotation speed of over 900 RPM.

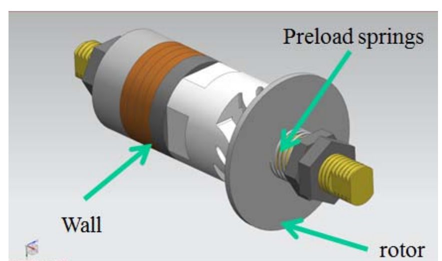


Flexure Fingers Horn



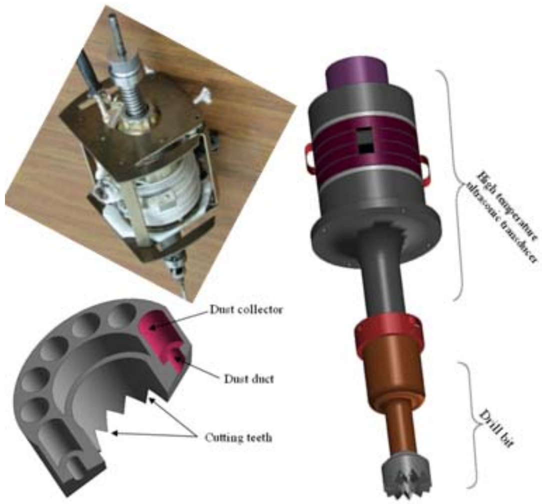


2-bar horn

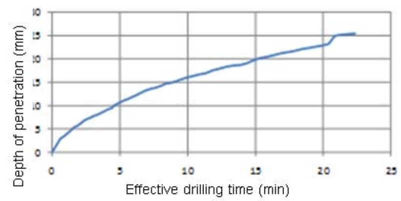


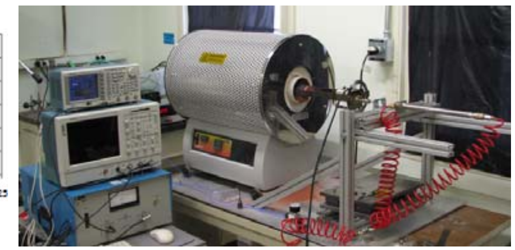
4-bar horn

The HT piezo-actuated USDC Sampler

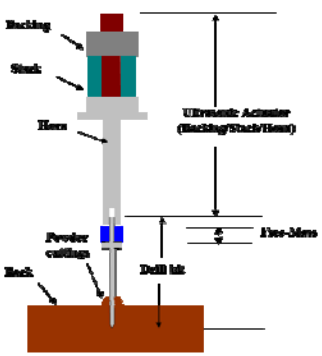


Under PIDDP, a USDC-based piezo-actuated rotary-hammering sampler has been developed that was demonstrated to penetrate 1" thick brick in 21-min accumulated time.

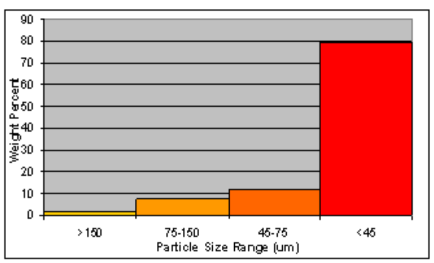




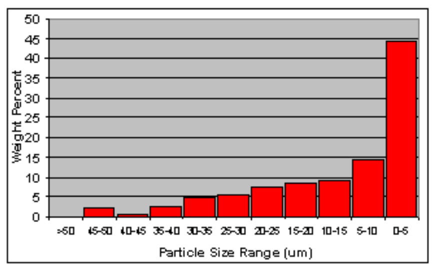
2000 R&D 100 award



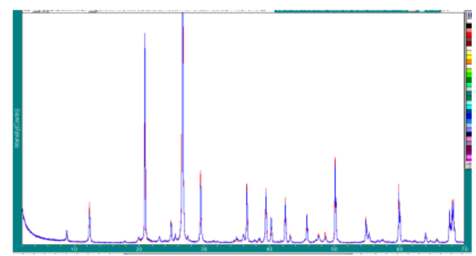
The USDC creates small particles that are ideal for XRD/XRF analysis



Size fractions obtained during wet sieving



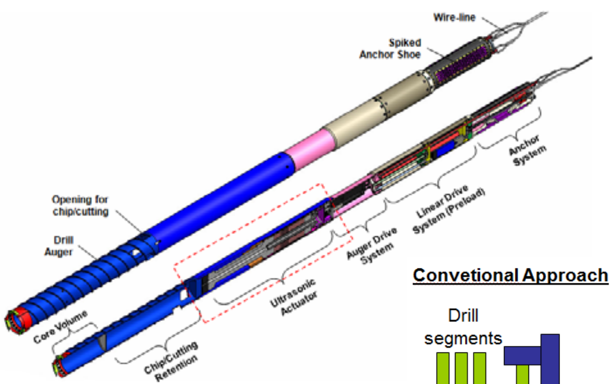
Particle size distribution of the <45μm powder obtained using a Horiba CAPA-500 particle size distribution analyzer.

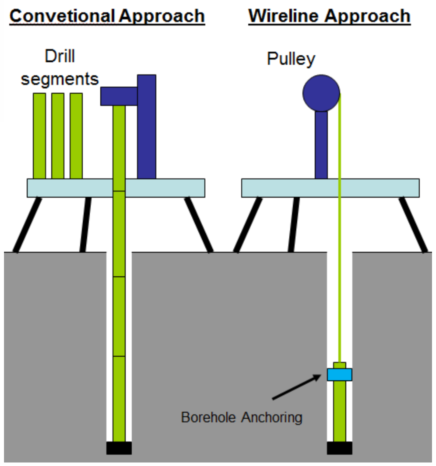


LANL's Lab XRD patterns of the <45 μ m USDC powder (blue) compared to the Retsch milled <5 μ m powder (red).
Note: The patterns compared extremely well.

Deep Drilling and Sampling via Auto-Gopher

The Auto-Gopher drilled over 3 m deep hole. The produced 32 rock cores are placed inside the 4 protective tubes shown in the photo.

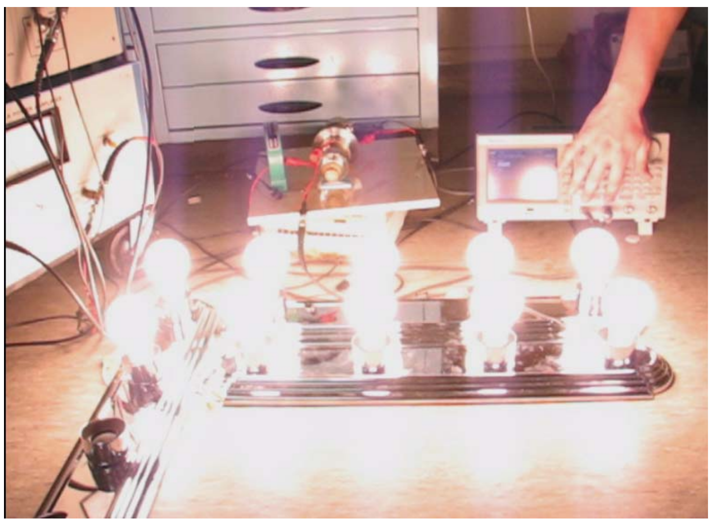




Conventional drill string vs. wireline drilling approach

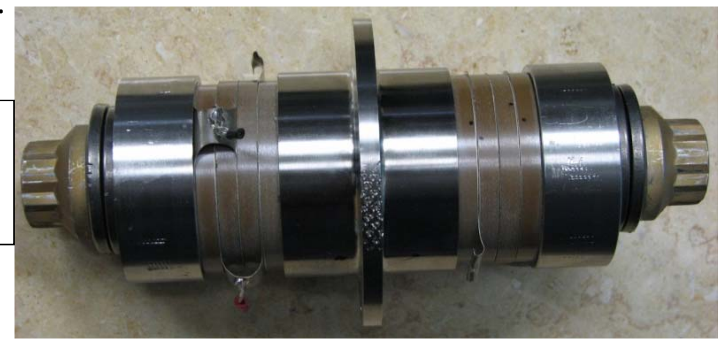
1 kW Power Transmission using Wireless Acoustic-Electric Feed-through

- A novel wireless transfer of 1KW power and data thru plates was developed and successful demonstrated in 2007 under the Advanced Concepts Program.
- This mechanism is based on the direct and converse piezoelectric effects as means of generating ultrasonic stress waves that are transmitted through walls where the received signal is converted to an electric signal across an impedance load.
- The developed system avoids the need for wires that can cause structural weakness or reduction of sealed containers ability to maintain pressure, vacuum, temperature or maintain chemicals and gasses.

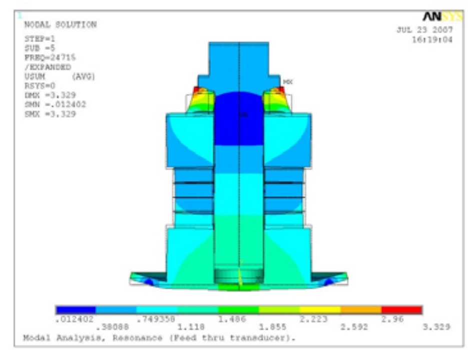


Ten 100W light bulbs (two groups of 5 serially connected bulbs) powered by the wireless transmission device.

Output power 1083W, Efficiency 84%

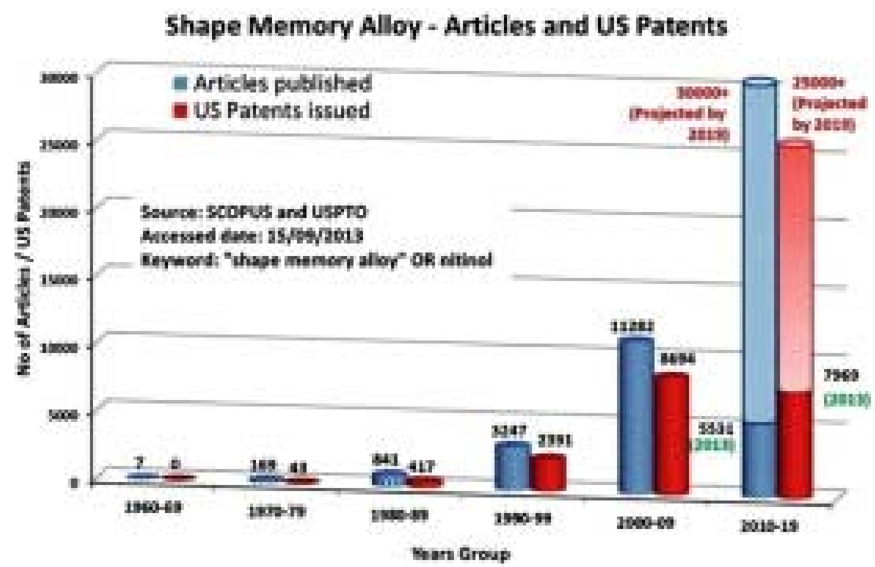


The analysis of the feed-thru at ~24 kHz asymmetric mode creates significant vibration amplitude on the wall.



Shape memory alloys

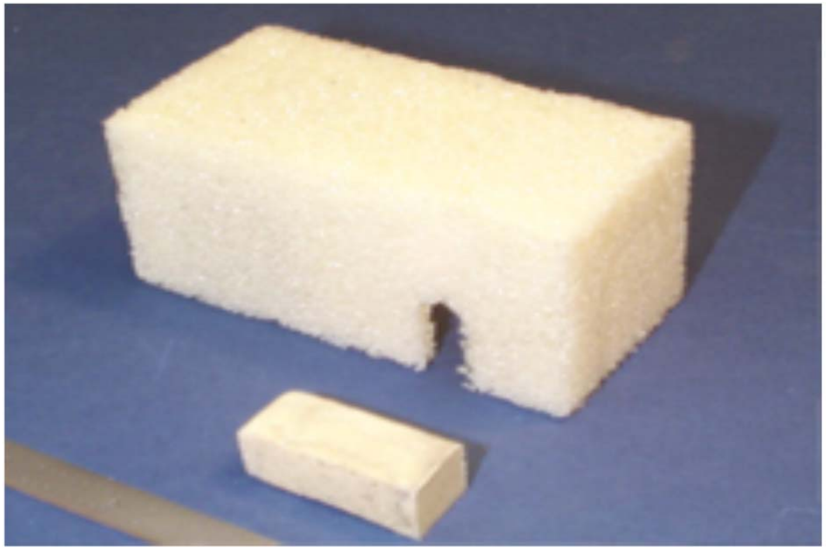
- Shape memory alloys act as actuators using their ability to display two distinct crystal structures or phases, which is a function of the temperature and internal stresses.
- At lower temperatures – an SMA is in its martensite form and the alloy can be easily deformed into any shape.
- When it is heated, its phase is transformed to austenite and it "remembers" the shape it had before it was deformed.
- Video showing a Nitinol Wire/Shape Memory Alloy in action https://www.youtube.com/watch?v=4Yi4epJ83EE



Ref.: J. M. Jani, M. Leary, A. Subic, and M. A. Gibson, "A review of shape memory alloy research, applications and opportunities", Materials & Design, Volume 56, (2014) pp. 1078 - 1113

Shape Memory Materials

- Shape memory materials are a class of smart materials that are able to recover a predetermined shape following environmental changes (e.g., thermal, chemical, magnetic) even after undergoing large deformations.
- There are two key sub-groups: Shape memory Alloys (SMA) and Shape Memory Polymers (SMP).



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

Electroactive Polymers (EAP)

FIELD ACTIVATED (ELECTRONIC) EAP

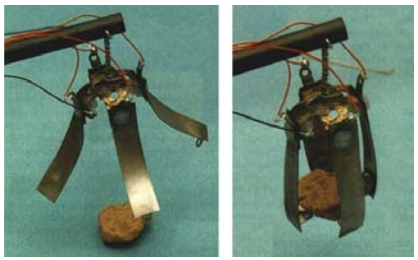
- Dielectric EAP
- Electrostrictive Graft Elastomers
- Electrostrictive Paper
- Electro-Viscoelastic Elastomers
- Ferroelectric Polymers
- Liquid Crystal Elastomers (LCE)

IONIC EAP

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

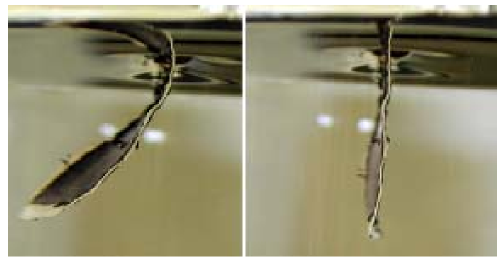
Ionic EAP

Turning chemistry to actuation



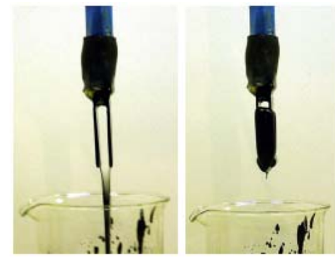
IPMC

[JPL using ONRI, Japan & UNM materials]



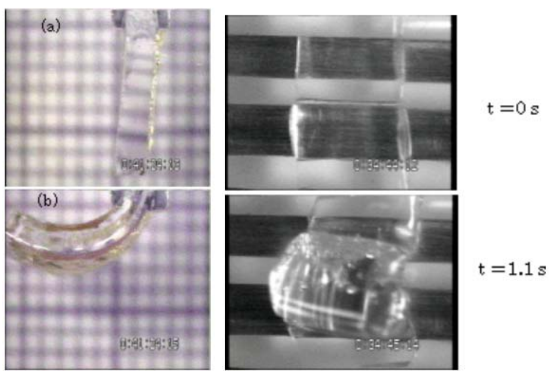
Conductive Polymers

[Made and photographed at JPL]



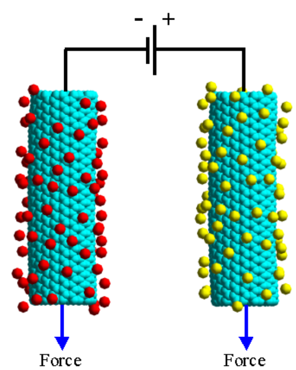
ElectroRheological Fluids (ERF)

[ER Fluids Developments Ltd]



Ionic Gel

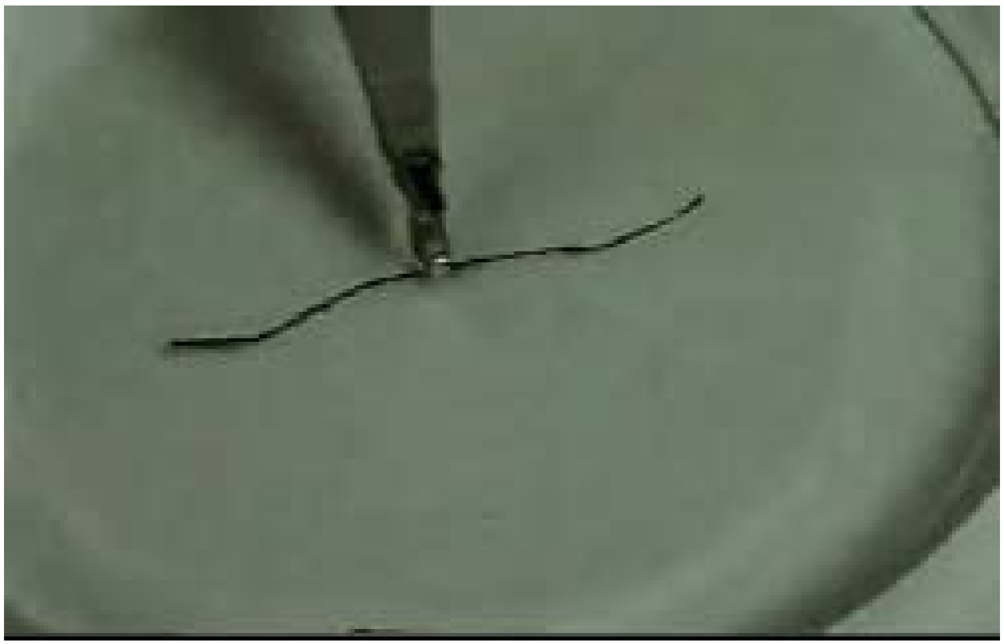
[T. Hirai, Shinshu University, Japan]



Carbon-Nanotubes

[R. Baughman et al, UTD]

EAP – as artificial muscles



IPMC made by Keizuke Oguro, ONRI, Japan

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

Exploration of planetary applications

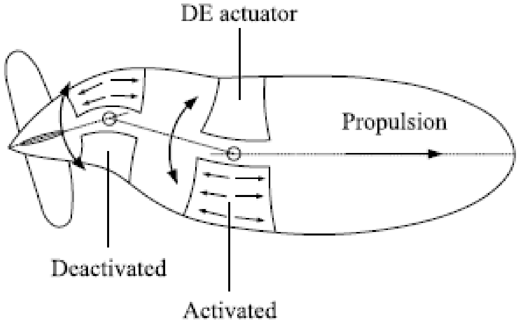
Dust wiper

Sample
handling
robotics

EAP driven blimps

Quiet blimp can operate as observation post and reconnaissance, as well as platform for various payloads.

EAP activated blimp



A graphic view of the EAP activated blimp propelled by wagging the body and tail just like a fish.
Courtesy of Silvain Michel, EMPA, Materials Science & Technology, Duebendorf, Switzerland.

Fish-like blimp that uses a wagging body and tail for propulsion and is actuated by dielectric elastomer EAP
Courtesy of Silvain Michel, EMPA, Switzerland. http://www.empa.ch/bilder/bilder-117/EAP-Betablimp_kurz.wmv

The First Arm-wrestling Contest

March 7, 2005

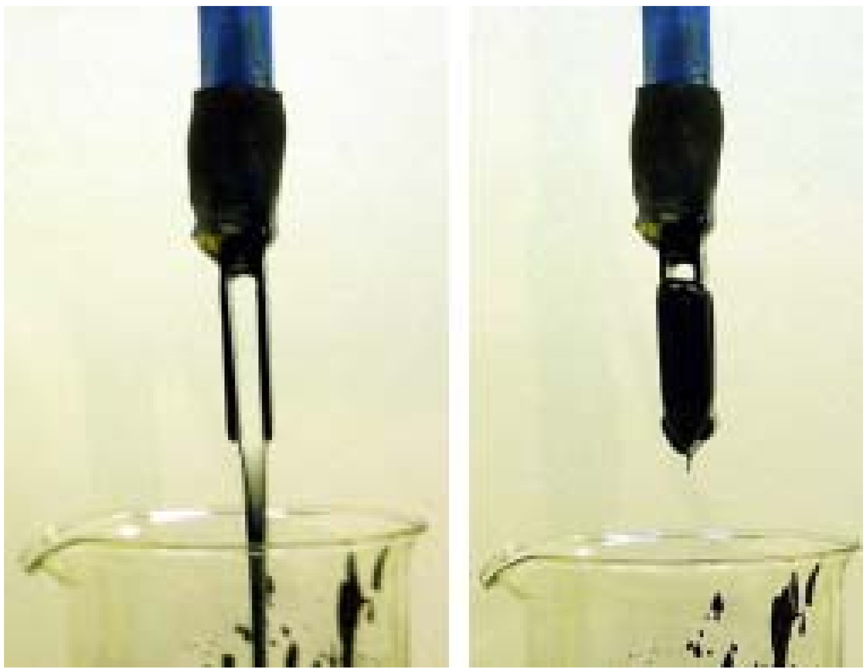
EMPA, Dubendorf, Switzerland used dielectric elastomer in 4 groups of multi-layered scrolled actuators– this arm lasted 4-sec.

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

Environmental Robots Inc. (ERI), Albuquerque, NM, used shape memory polymer strips.

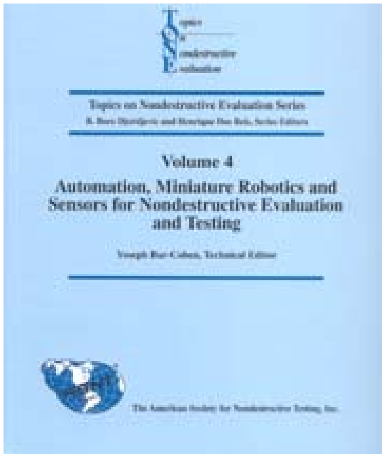
Electro-Rheological Fluid

- Suspension of particles in an insulating base fluid
- The viscosity Changes when subjected to an electric field. The response is in milliseconds.

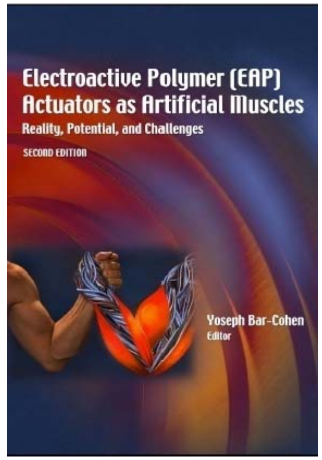


At reference (left) and activated states (right).
[Smart Technology Ltd, UK]

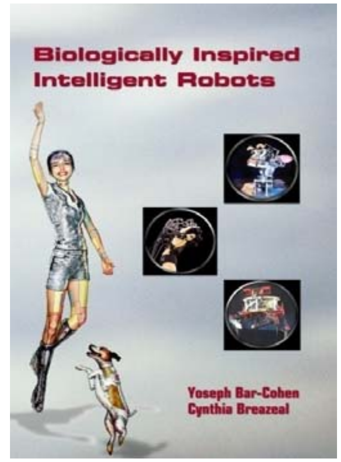
Video



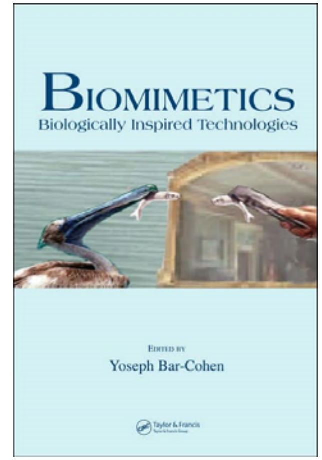
2000



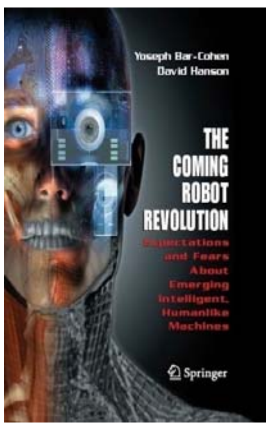
1st Ed. (2001)
2nd Ed. (2004)



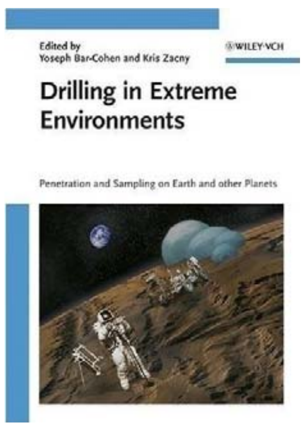
2003



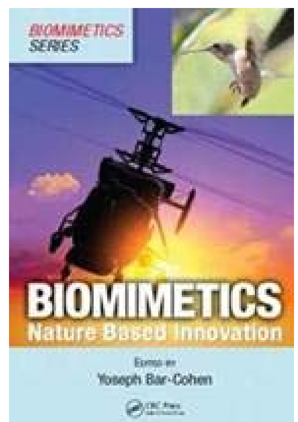
2005



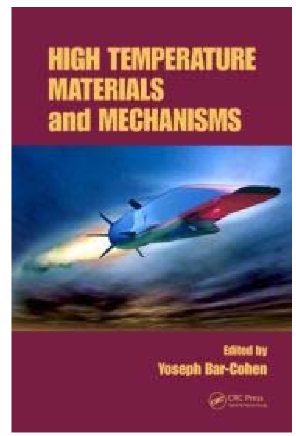
2009



2009



2011



2014

Low Temperature Materials and Mechanisms

2015

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

Acknowledgement

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