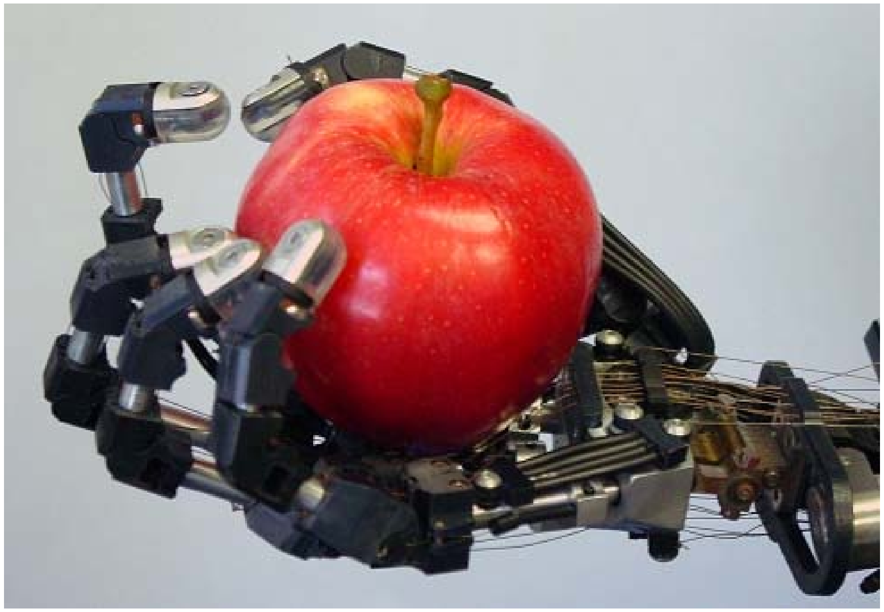
Biomimetic Sensors and Actuators



Yoseph Bar-Cohen, PhD
Senior Research Scientist & Group Supervisor, JPL/Caltech/NASA,
yosi@jpl.nasa.gov,   http://ndeaa.jpl.nasa.gov

UIA Symposium, San Francisco, CA
April 16, 2012


Topics on Nondestructive Evaluation Series

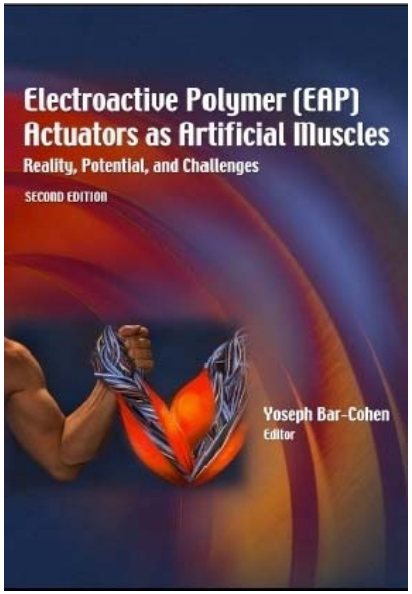
Volume 4

Automation, Miniature Robotics and Sensors for Nondestructive Evaluation and Testing

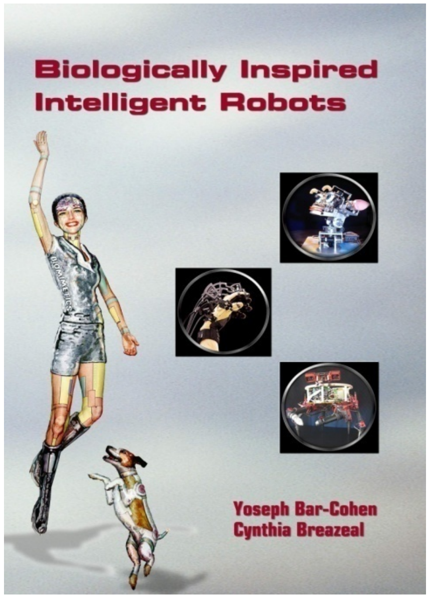
Yoseph Bar-Cohen, Technical Editor

The American Society for Nondestructive Testing, Inc.

2000



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



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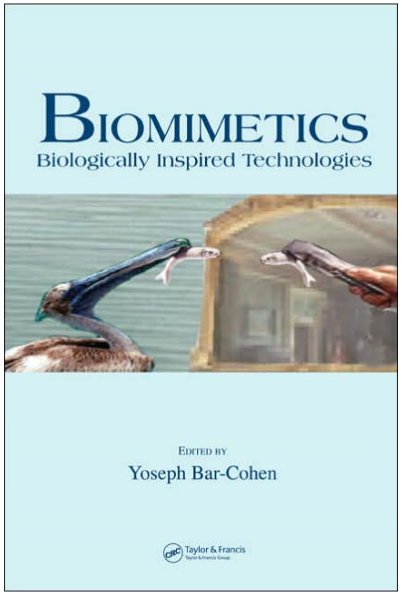

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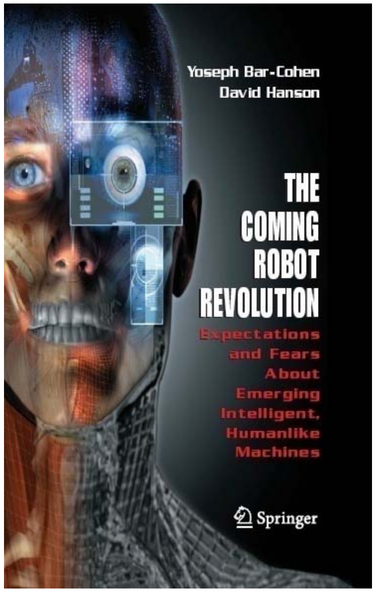
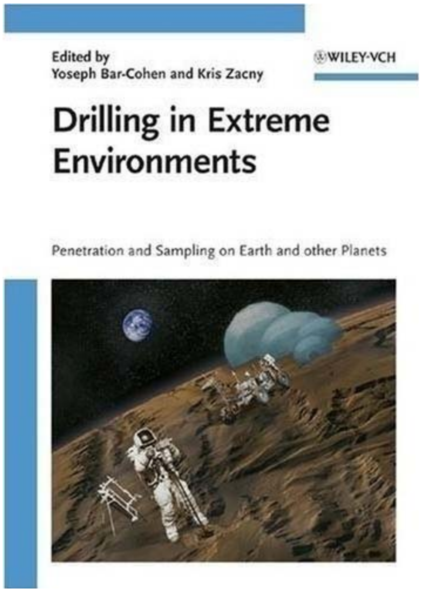
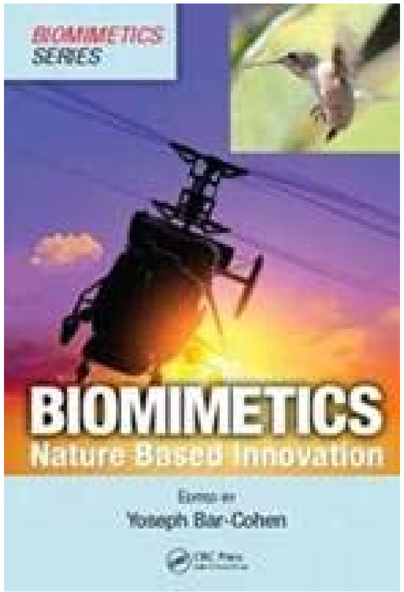
2009





2011



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

Nature as a model for human innovation

- Nature is the biggest experimental lab that has ever exited and ever will.
- Thru trial and error experiments it is addressing its challenges and coming up with inventions that work.
  - Only the solutions that lasted are in our surrounding today.
- Nature has always inspired human innovation and achievement.
  - Mimicking nature led to effective materials, structures, tools, mechanisms, processes, algorithms, methods, systems and many other benefits.
- Nature has enormous pool of inventions for inspiriting future innovation.
  - Since increasingly we are improving our tools, there are many more capabilities that we can mimic.

Why mimic nature?

Biology – inspiring human innovation

Flying was enabled using aerodynamic principles

Honeycomb structures are part of almost every aircraft

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

The octopus as a model for biomimetics

Adaptive shape, texture and camouflage of the Octopus

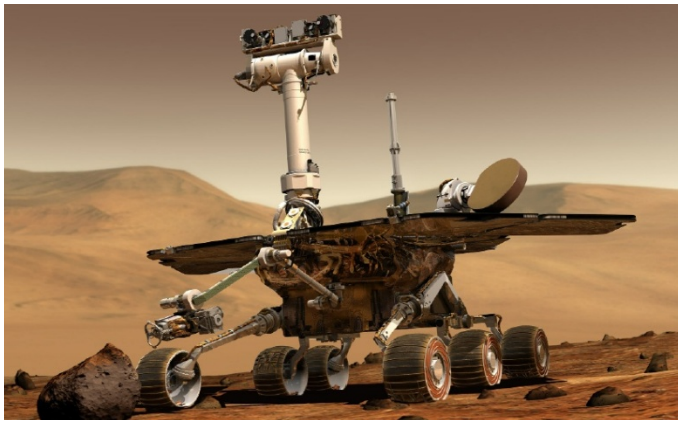
Courtesy of William M. Kier, of North Carolina

Courtesy of Roger T. Hanlon, Director, Marine Resources Center, Marine Biological Lab., MA

Plants use of camouflage

- To maximize the chances of pollination - flowers are as visible as possible.
- To protect from premature damage – initially fruits are green, have sour taste, and are camouflaged by leaves.
- Once ripped, fruits become colorful and tasty, as well as have good smell

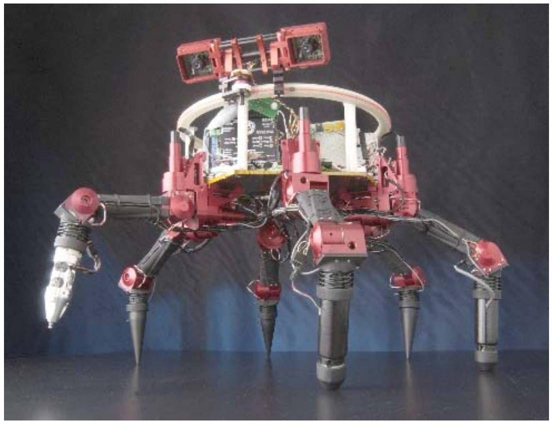
Robotic exploration of the universe



Mars Exploration Rover
(two landed on Mars in Jan 2004)

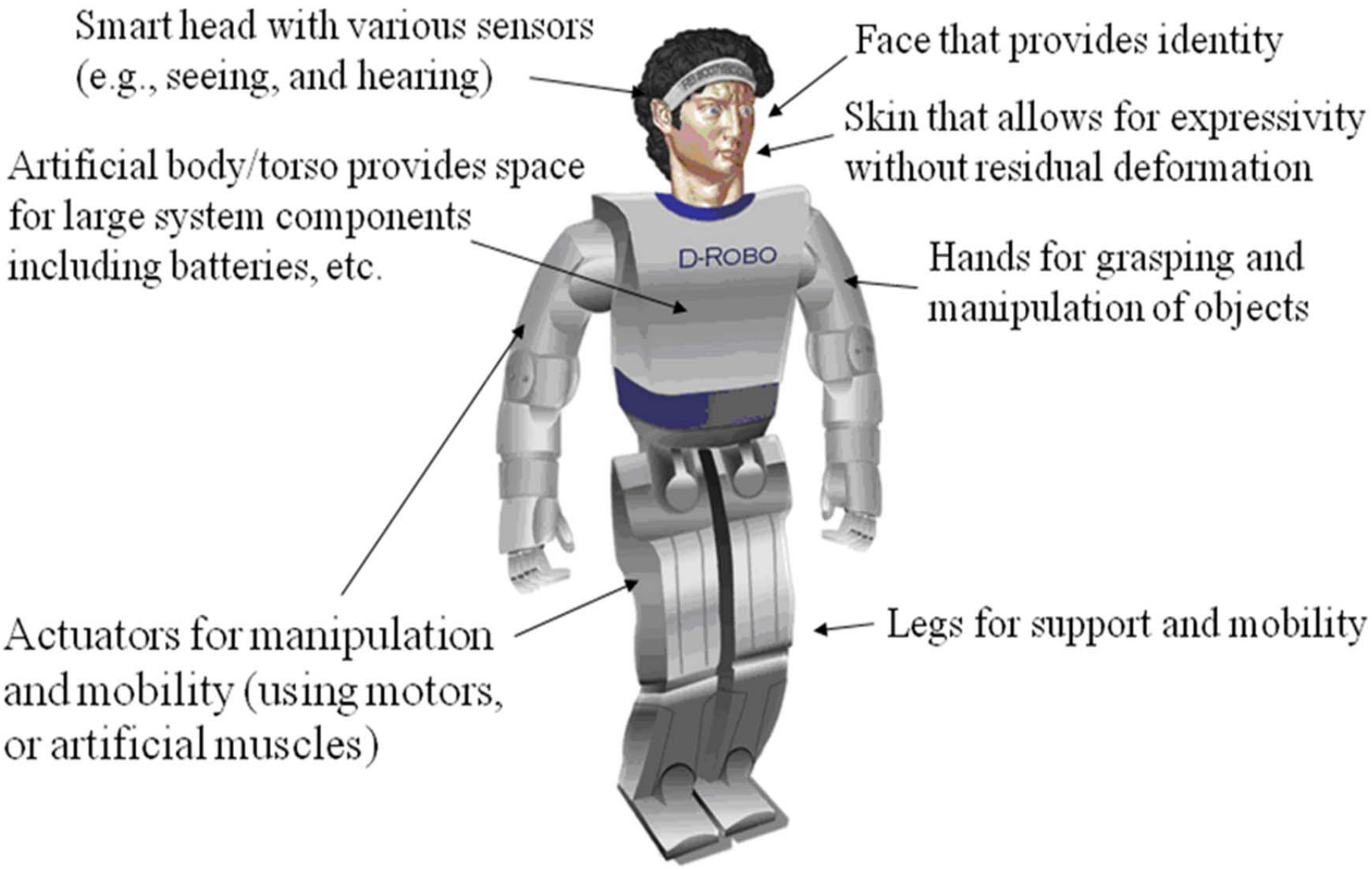
The mountain goat is an inspiring model for all-terrain legged rovers

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



A futurist vision of the role of humanlike robots in planetary exploration of the Universe

Making humanlike robot



Smart head with various sensors (e.g., seeing, and hearing)

Face that provides identity

Skin that allows for expressivity without residual deformation

Artificial body/torso provides space for large system components including batteries, etc.

Hands for grasping and manipulation of objects

Actuators for manipulation and mobility (using motors, or artificial muscles)

Legs for support and mobility

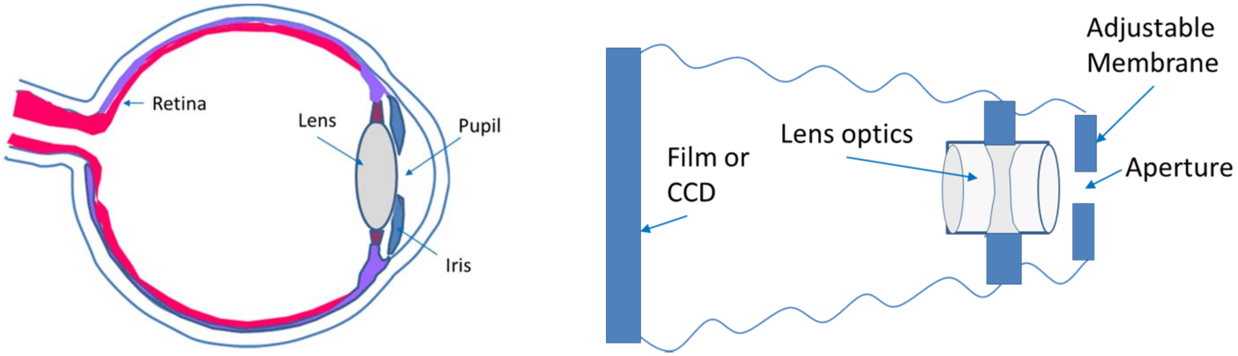
The image is a courtesy of Adi Marom, graphic artist.

Sensors and senses

Camera and the eye

- The eye is an optical device with characteristics that are similar for many creatures.
- Biomimetic applications include specialized detectors, navigation systems surveillance, cameras and even visual prosthetics.

Eyes of various biological bodies including from left to right: land snail, squirrel, crocodile and human

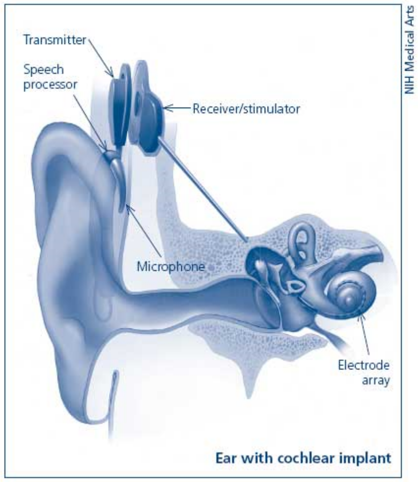


Mimicked senses include the vision in the form of cameras: camera shutter – eyelid; aperture - pupil; adjustable diaphragm - iris; photographic film or charge-coupled device (CCD) - retina.

Hearing and sonar imaging using sound

- Hearing is the most important sense for protection against potential danger - missing an indication of approaching predator my be too late once seeing.
- The ears receive sound waves and analyze them to warn against dangers, alert of approaching predator, provide communication queues, and allows comprehending speech.
- It is far superior to any human-made sensors (bandwidth, sensitivity and resolution).
- There are many ear shapes even within the same species.
- Advancement led to the development of effective cochlear implants providing deaf people an electrical stimulation directly to the auditory nerve, bypassing the damaged cochlea that causes the deafness.

Ears of various species can vary significantly in shape.



Schematic view of the human ear with a cochlear implant. Credit: Medical illustrations by NIH, Medical Arts & Photography Branch.

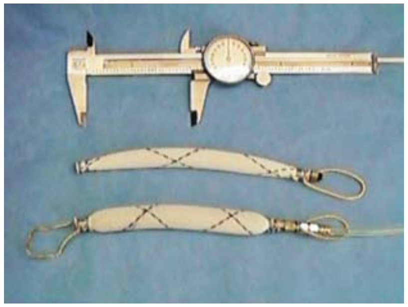
EAP historical perspective

- 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.

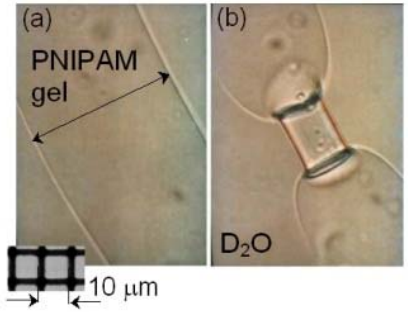
* Electrets are dielectric materials that can store charges for long times and produce field variation in reaction to pressure.

Non-Electrical Activatable Polymers

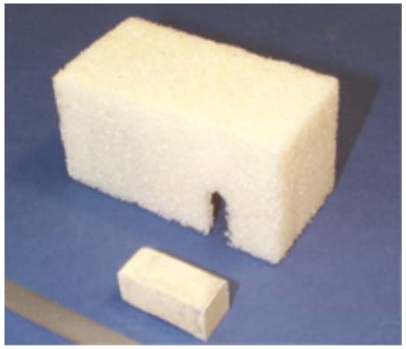
- Chemically Activated
- Shape Memory Polymers
- Inflatable Structures
- Light Activated Polymers
- Magnetically Activated Polymers



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



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



Shape Memory Polymers
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

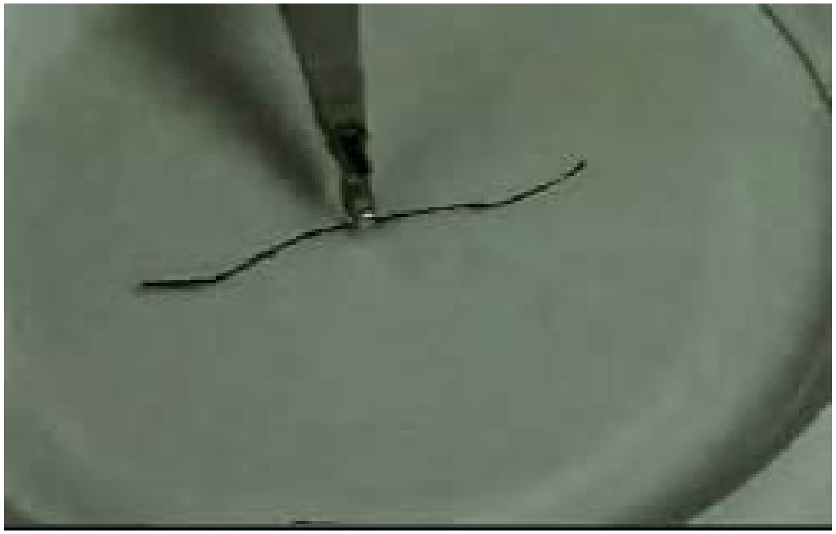
- Carbon Nanotubes (CNT)
- Conductive Polymers (CP)
- ElectroRheological Fluids (ERF)
- Ionic Polymer Gels (IPG)
- Ionic Polymer Metallic Composite (IPMC)

Comparison between EAP and widely used 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.

EAP – as artificial muscles

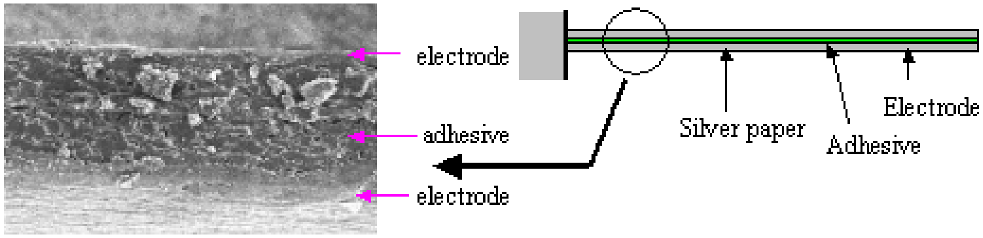


IPMC made by Keizuke Oguro, ONRI, Japan

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

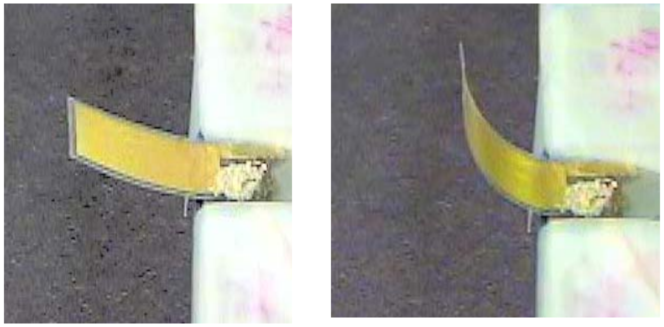
Electric Field Activated EAP

Electric Field or Coulomb Forces Driven Actuators



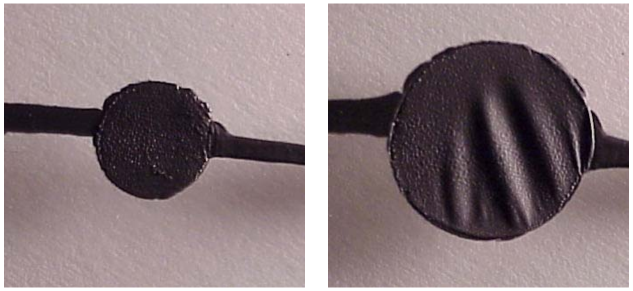
Paper EAP

[J. Kim, Inha University, Korea]



Ferroelectric

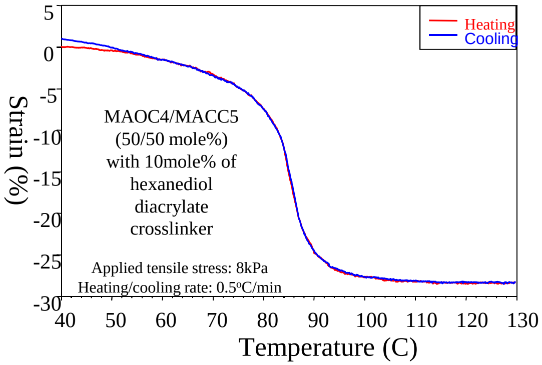
[Q. Zhang, Penn State U.]



Voltage Off **Voltage On**

Dielectric EAP

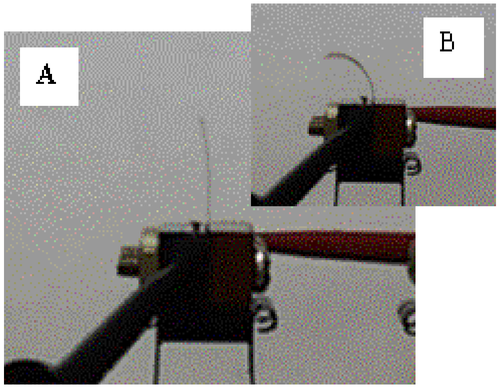
[R. Kornbluh, et al., SRI International]



Liquid crystals

(Piezoelectric and thermo-mechanic)

[B. R. Ratna, NRL]

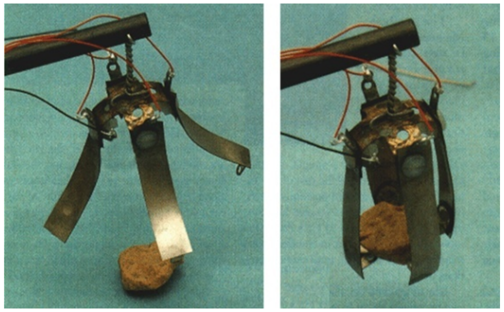


Graft Elastomer

[J. Su, NASA LaRC]

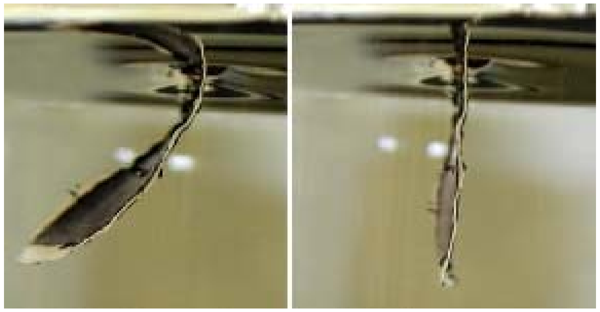
Ionic EAP

Turning chemistry to actuation



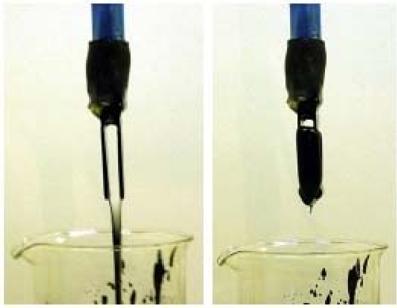
IPMC

[JPL using ONRI, Japan & UNM materials]



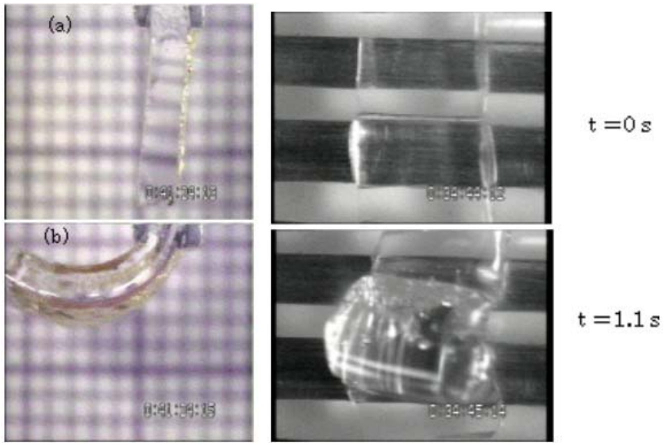
Conductive Polymers

[Made and photographed at JPL]



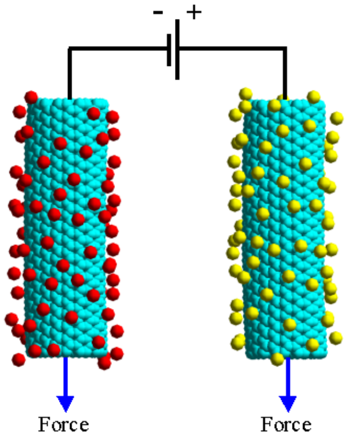
ElectroRheological Fluids (ERF)

[ER Fluids Developments Ltd]



Ionic Gel

[T. Hirai, Shinshu University, Japan]



Carbon-Nanotubes

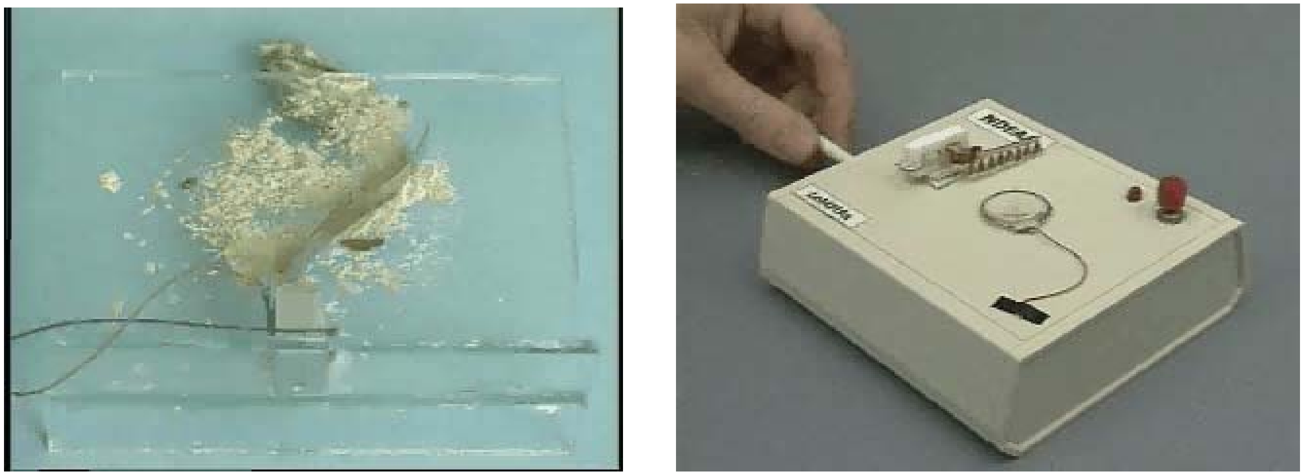
[R. Baughman et al, Honeywell, et al]

Current EAP
Advantages and disadvantages

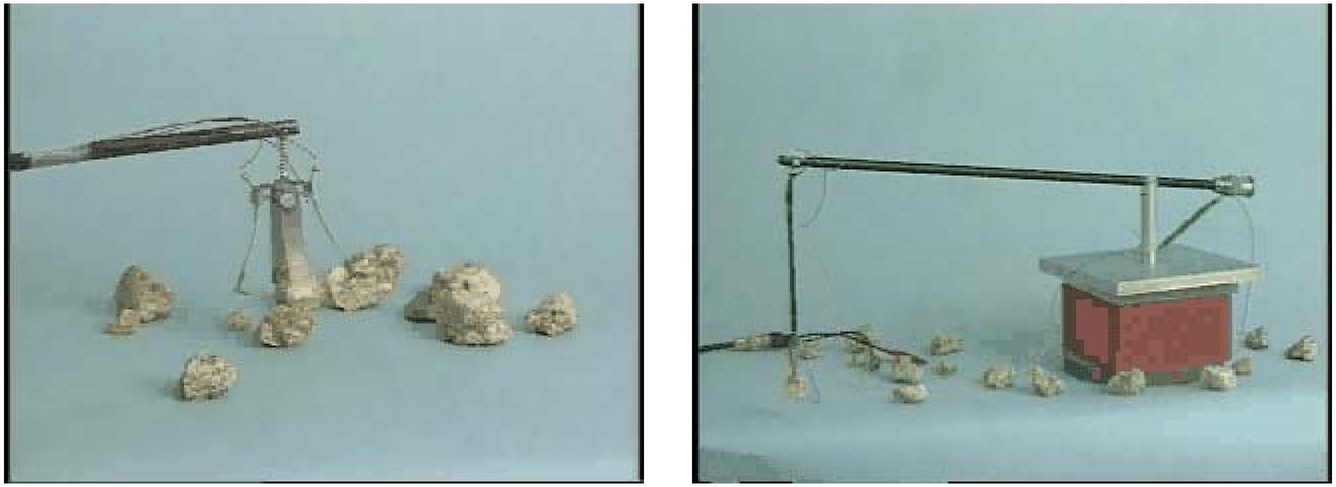
EAP type	**Advantages**	**Disadvantages**
Field Activated (Electronic) EAP	• Can operate in room conditions for a long time • Rapid response (msec levels) • Can hold strain under dc activation • Induces relatively large actuation forces	• Requires high voltages (~150 MV/m). Recent development allowed 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.

Exploration of planetary applications

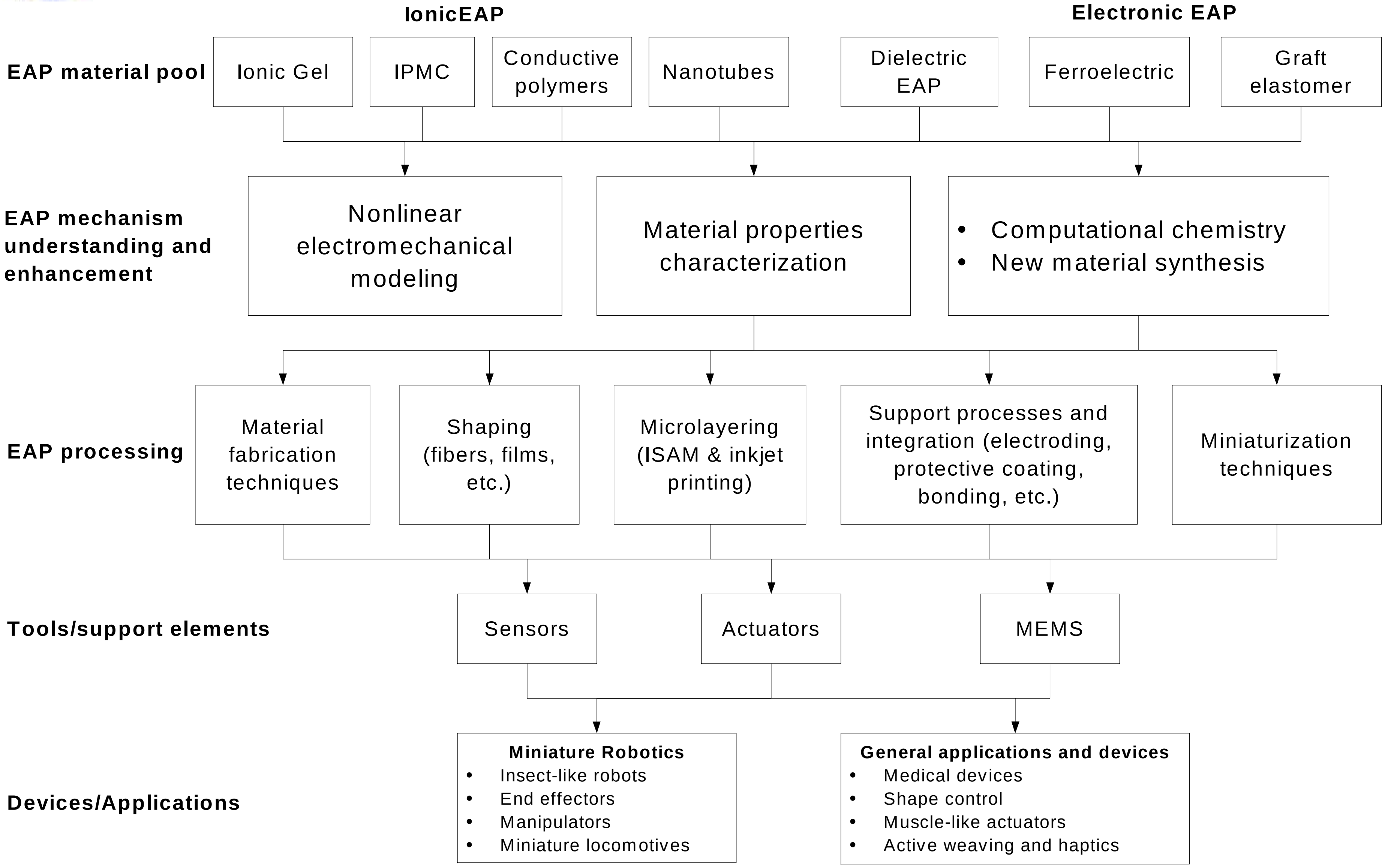
Dust wiper



Sample handling robotics



EAP infrastructure



IonicEAP

Electronic EAP

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

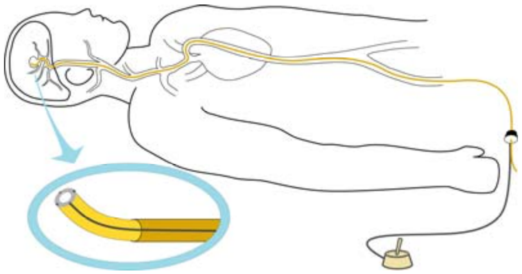
Miniature Robotics
- Insect-like robots
- End effectors
- Manipulators
- Miniature locomotives

General applications and devices
- Medical devices
- Shape control
- Muscle-like actuators
- Active weaving and haptics

Medical Applications

Cyborgs potentials for EAP actuators

G. Whiteley, Sheffield Hallam U., UK



Catheter Guide Using IPMC

K. Oguro, ONRI, Japan

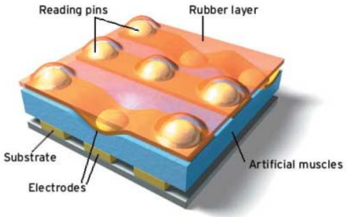
Smart pill that can crawl inside the gastronomical track

EAP based microanastomosis connector
Micromuscle, Sweden

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

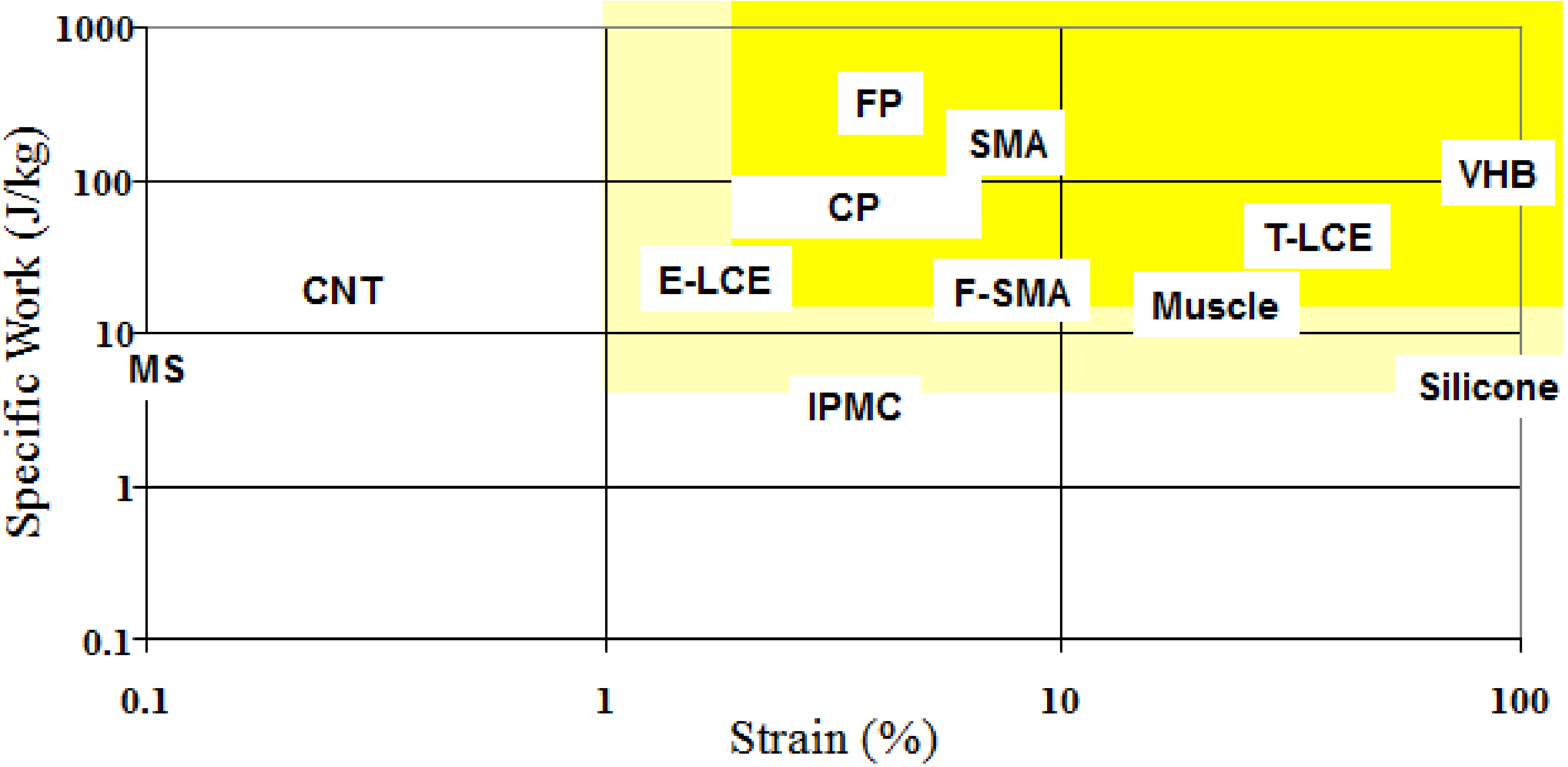


Active Braille Display

Concerns and requirements

- No established database or standard test procedures
- Need to identify application to devices within the performance capability of current EAP
- There are lifetime and reliability issues
- It is not obvious how to scale EAP making very large or very small actuators
- There is a need for niche applications

Strain and Work Density



SMA – Shape memory alloy
CP – Conducting polymer
FP – Ferroelectric polymer
MS – Magnetostrictive
IPMC – Ionic Polymer/Metal Composite

F-SMA – Ferromagnetic SMA
Muscle – Mammalian Skeletal Muscle
Silicone – Dielectric Elastomer
VHB – Dielectric Elastomer
T-LCE – Thermal Liquid Crystal Elastomer
E-LCE – Thermal Liquid Crystal Elastomer

Credit: John Madden, U. of British Columbia, Vancouver, Canada

The grand challenge for EAP as

Artificial Muscles

Wrestling match between EAP actuated robotic arm and human

The performance of the human arm is 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 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.

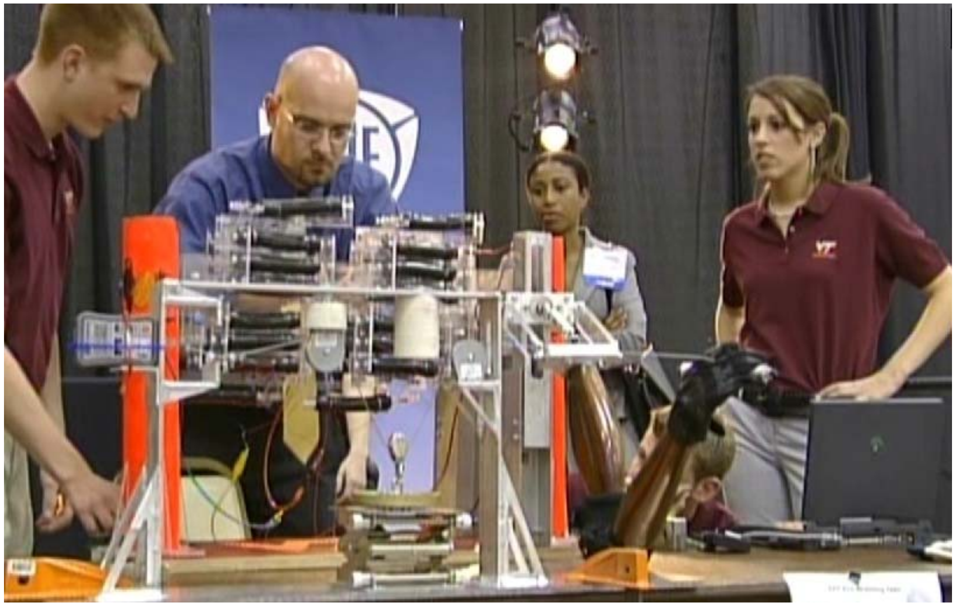
Environmental Robots Inc. (ERI), Albuquerque, NM, used shape memory polymer strips.

The 2nd Armwrestling Contest (2006)

Strongest arm

Human as baseline

Fastest arm



Major accomplishments for the field

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

CANCER-KILLING VIRUSES • DANGEROUS MELTING IN THE ARCTIC

SCIENTIFIC AMERICAN

China The Next Space Superpower

ARTIFICIAL MUSCLES

Shape-Shifting Plastics Replace Motors in Machines That Move

Star Clusters Born of Galactic Collisions

The Economics of Child Labor

Protecting Farms against Agricultural Terrorism —see page 28

Oct. 2003 - Cover page of Scientific American

2003 - Multifunctional Electroelastomer Roll (MER) Spring Roll (SRI International)

March 2007 - Made by EMPA, a large scale application of EAP in steering a 3 m blimp long

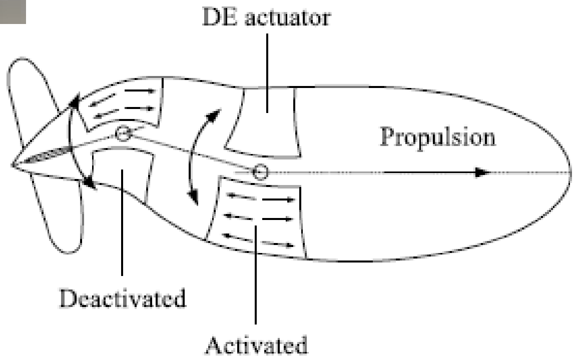
March 7, 2005 - The first arm wrestling arm competition. 3 EAP arms wrestled with a 17-year old student and the student won all three.

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/plugin/template/empa/*/72289/---/l=1#s5a]

Making a humanlike robot intelligent

There are three key possibilities of making a humanlike robot operate intelligently:

- Telepresence, e.g., Robonaut.
- Fully autonomous humanlike robots with instilled cognition.
- Cyborg using natural human brain controlling a humanlike machine. The technology is too far from today's capability.

Robonaut is either autonomous or remotely controlled by a human user via telepresence.

Why make humanlike robots?

Why our size and shape?

We, the human species, built the world around us in a way that is ideal for our size, shape and capabilities, allowing everything in our daily life to fit our human form.

- Copying our size allows a robot to reach the door handle, see us at eye-to-eye level, climb stairs, sit on our chair, repair and maintain our tools and appliances, enter our car and possibly drive it, and perform many other support tasks that we can do.

Need for the size of a human hand.
Courtesy of Graham Whiteley, Elumotion, UK.

Why to enable facial/body and verbal expressions?

Since we respond intuitively to body language and gestures it makes the robot more communicative and sociable if it uses facial and body expressions while expressing itself verbally.

Facial expressions
Made by David Hanson, Hanson Robotics.

Historical perspective

- Leonardo da Vinci is attributed as the first (~1495) to sketch a humanlike mechanical form (i.e., knight) that could sit, wave its arms, and move its head.
- The marionettes are the precursor to the modern HLR.
- The French engineer and inventor, Jacques de Vaucanson, is credited as the first to produce a physical machine that appears and acts like a human. In 1737, he produced the "Flute Player” that is life-size mechanical figure that played a flute.
- Another famous humanlike machine is the “Writer”. It was completed by the Swiss clockmaker Jacquet-Droz in 1772 and it is able to write custom text.

The marionettes were originated in France in medieval times

Model of Leonardo's robot and its inner working components.
Courtesy: Public domain graphics per Wikipedia

The “Writer” was created by Pierre Jaquet-Droz, 1772.
Courtesy of the Musée d'art et d'histoire, Neuchâtel Switzerland

Humanoid robots - distinguishable features

The PINO humanoid has a machine appearance with human characteristics

Courtesy of Kitano Symbiotic Systems, Japan

The Fujitsu’s “enon” robot

Courtesy of Fujitsu Frontech Limited and Fujitsu Laboratories Ltd., Japan

Female Type (FT)

Courtesy of Tomotaka Takahashi, Robo-Garage, Kyoto, Japan

The Robo-Garage’s Chroino

Photographed by the author

Realistically looking humanlike robots

Courtesy of Hiroshi Ishiguro and his group at Osaka University jointly with Korkoro Co., Ltd.

The Cyber-receptionist Ms. Saya

Courtesy: Hiroshi Kobayashi, Tokyo University of Science.

EveR-2 Muse

Courtesy of KITEC (Korea Institute of Industrial Technology).

The roboticists Zou Renti, China, and his clone robot at Nextfest 2007.

“Beauty contest” of humanlike robots

Potential candidates for future robotic beauty pageant

Actroid-DER 01(made by Kokoro, Inc.)

Actroid-DER 02
(made by
Kokoro, Inc.)

Replee Q2 facing the graduate student Motoko Noma in Tokyo

Courtesy of Osaka University

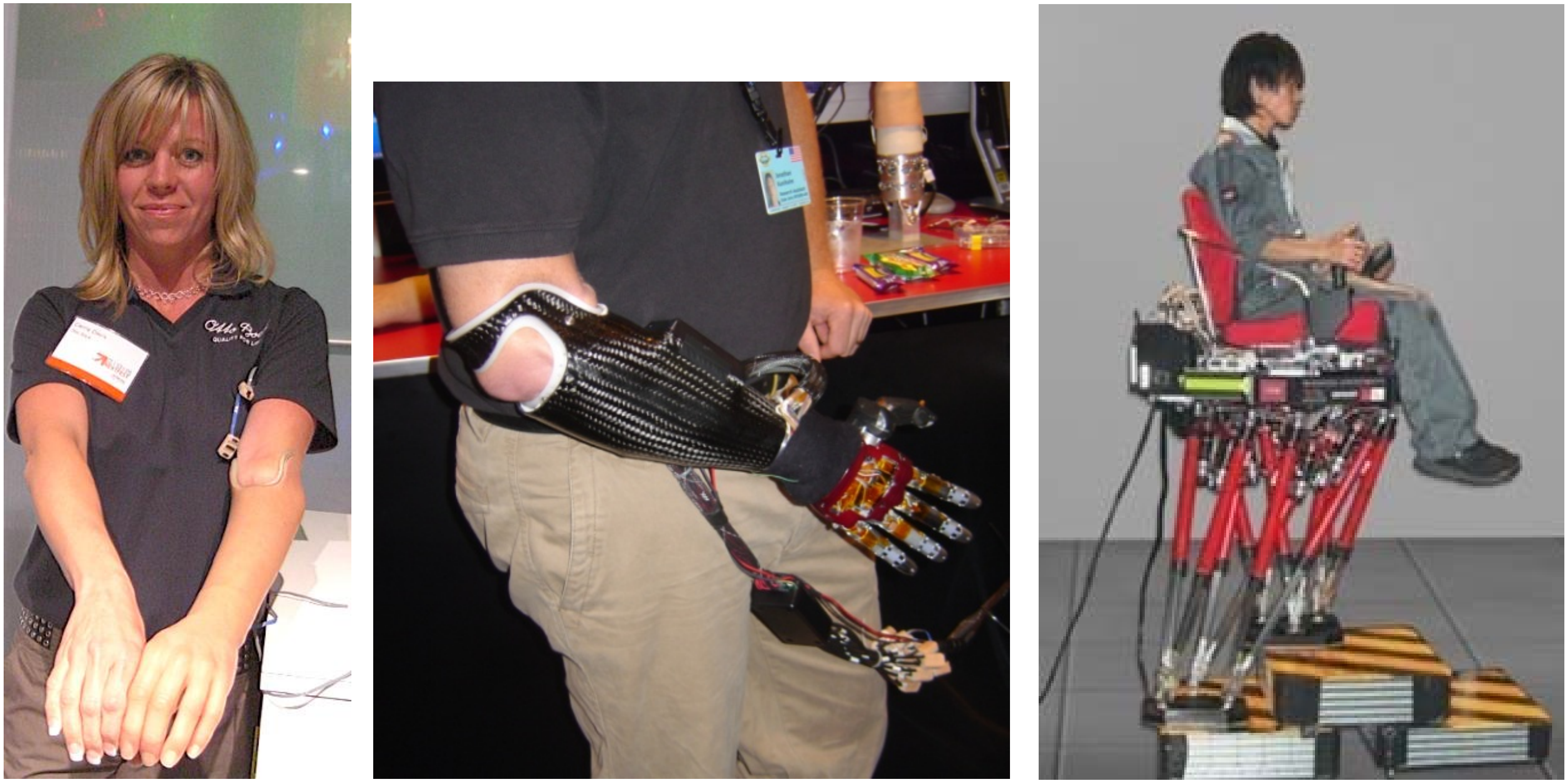
Dion is a humanlike robot made in China.

Realistic prosthetics

Prosthetics are increasingly becoming more lifelike. The technology reached the level that, during the 2008 Olympics games in China, the South African athlete Oscar Pistorius (having two prosthetic legs) sought to participate as a runner in a race against able-bodied athletic runners with natural legs.

Courtesy of Fatronik, San Sebastian.

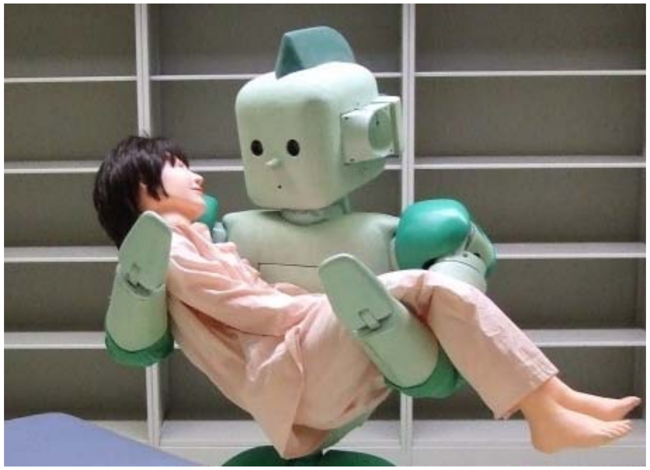
Prosthetics, exoskeletons and walking seats



Potential applications of HLR

Humanoids and HLRs are already being made to look like and operate as receptionists, guards, hospital workers, guides, dancers, toys, and more.

- High risk jobs - Filling need for employees to perform dangerous, and physically demanding jobs.



The RI-MAN robot carries a manikin as a simulated patient.
Courtesy: RIKEN Bio-Mimetic Control Research Center, Japan.

- Entertainment – movies, toys, partner in sport (tennis, etc.).

- Medical – Perform surgeries, support healthcare staff, assist in rehabilitation and perform psychological therapies including phobia (e.g., treatment of autism, fear of speaking in public, etc.) and provide smart prosthetics.
  - For elderly, disabled or patients in rehabilitation, HLRs robots may provide assistance, monitoring, and emergency treatment 24-hours 7-days a week at their own home.

Courtesy – Adi Marom, Graphic Artist.

Fears and potential dangers

- There is a growing concern that HLR will be used to perform improper or unlawful acts.
  - Rapid prototyping of specific humans may become the ultimate identity theft.
- Issues related to non-obedient robots or unacceptable behavior need attention.
- Preferably, HLR will be designed to interact with humans in master-slave relations possibly following the laws of the well-known science fiction writer, Isaac Asimov.
- Roboticists are already working on establishing rules of ethics for the developers and operators of HLR.
- Some of the phobia of HLR may be reduced once we find them more useful in our households and businesses.

Isaac Asimov

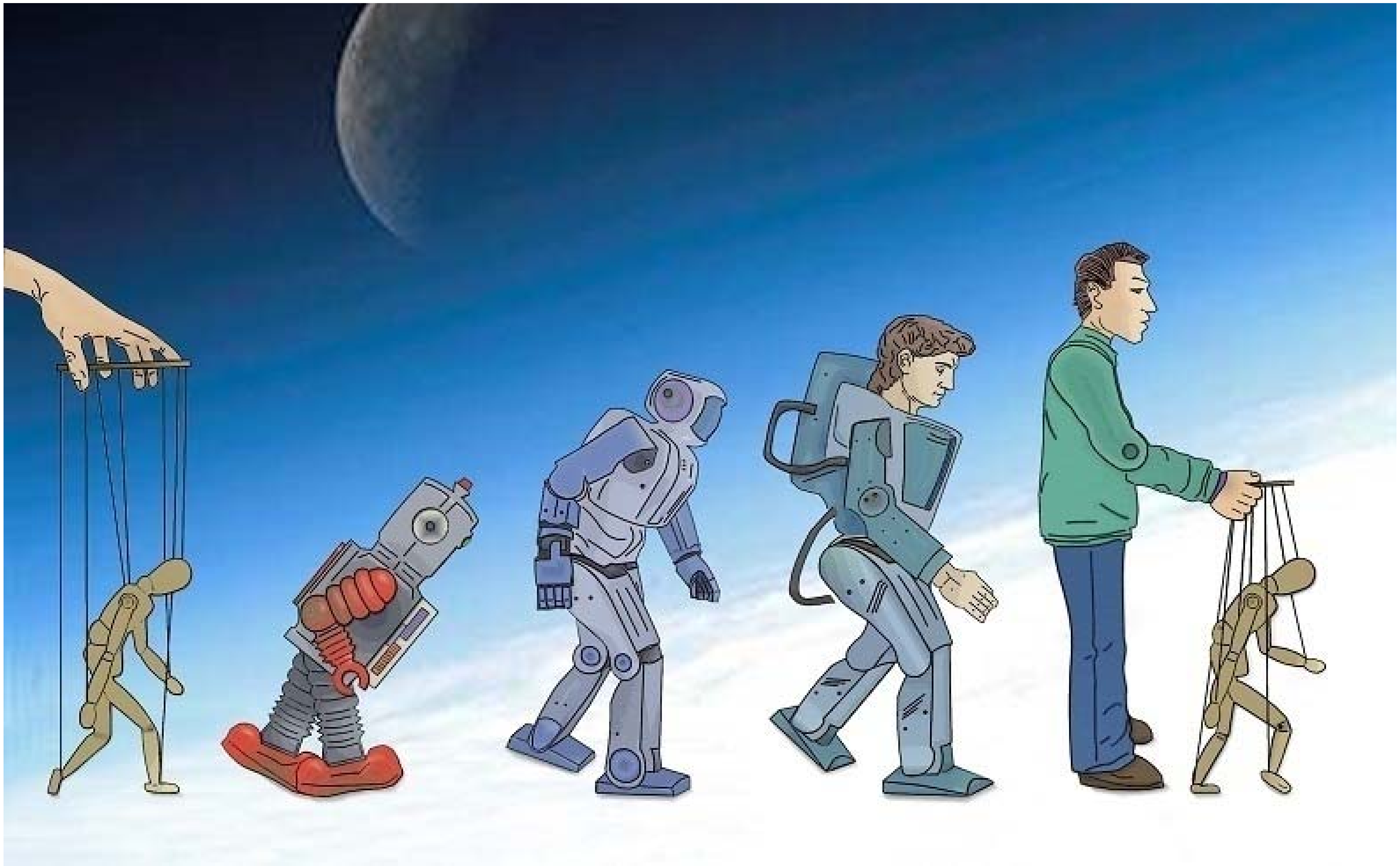
a.

b.

Image b. is a courtesy of David Hanson, Hanson Robotics

Futurist vision of one of the risks of an HLR being equipped with artificial cognition

Courtesy – Adi Marom, Graphic Artist.



Ref.: Y. Bar-Cohen & D. Hanson "Humanlike Robots" 2009.
Courtesy of Adi Marom, Graphics Artist.