Biomimetics

Biologically Inspired Technologies

1. Introduction

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.

Introduction

- Nature is the world's biggest experimental laboratory that ever existed and ever will.
- Over billions of years, trial and error experiments were conducted in every branch of engineering and science leading to the best and largest pool of inventions that work, last and continue to evolve.
- Nature's designs and capabilities have always inspired technology, and numerous examples can be listed including the use of tongs and tweezers as well as genetic algorithms and autonomous legged robots.
- This course is base on the instructor's recently published book entitled "Biomimetics – Biologically Inspired Technologies"
  - A system perspective is being taken examining the field from various angles to inspire biomimetic innovation
  - Looking inward at biological systems, the course covers the topics of biomimetic materials, structures, control, cognition, artificial muscles, biosensors that mimic senses, artificial organs, and interfaces between engineered and biological systems.

Biomedical Engineering

BIOMIMETICS

Biologically Inspired Technologies

EDITED BY

Yoseph Bar-Cohen

Nature is the world's foremost designer. With billions of years of experience and boasting the most extensive laboratory available, it conducts research in every branch of engineering and science. Nature's designs and capabilities have always inspired technology, from the use of tongs and tweezers to genetic algorithms and autonomous legged robots. Taking a systems perspective rather than focusing narrowly on materials or chemistry aspects, **Biomimetics: Biologically Inspired Technologies** examines the field from every angle.

This book contains pioneering approaches to biomimetics including a new perspective on the mechanization of cognition and intelligence, as well as defense and attack strategies in nature, their applications, and potential. It surveys the field from modeling to applications and from nano- to macro-scales, beginning with an introduction to principles of using biology to inspire designs as well as biological mechanisms as models for technology. It discusses evolutionary robotics; genetic algorithms; molecular machines; multifunctional, biological-, and nano- materials; nastic structures inspired by plants; and functional surfaces in biology. Looking inward at biological systems, the book covers the topics of biomimetic materials, structures, control, cognition, artificial muscles, biosensors that mimic senses, artificial organs, and interfaces between engineered and biological systems. The final chapter contemplates the future of the field and outlines the challenges ahead.

Harnessing the benefits of nature's vast experience, this book...

- Provides a wide-ranging view of numerous applications of biomimetics across a variety of fields
- Represents the latest advances from leading experts in their respective fields from around the world
- Examines the principles of modeling based on biology and the biological systems and mechanisms suited to imitation
- Explores biomimetics and biologically inspired concept, designs, and mechanisms

Featuring extensive illustrations, including a 32-page full-color insert, **Biomimetics: Biologically Inspired Technologies** provides unmatched breadth of scope as well as lucid illumination of this promising field.

Taylor & Francis
Taylor & Francis Group
A CRC PRESS BOOK
www.taylorandfrancisgroup.com

6000 Broken Sound Parkway, NW
Suite 300, Boca Raton, FL 33487
270 Madison Avenue
New York, NY 10016
2 Park Square, Milton Park
Abingdon, Oxon OX14 4RN, UK

3163
ISBN 0-8493-3163-3
90000
9 780849 331633

BIOMIMETICS
Biologically Inspired Technologies

EDITED BY
Yoseph Bar-Cohen

CRC
Taylor & Francis

BIOMIMETICS
Biologically Inspired Technologies

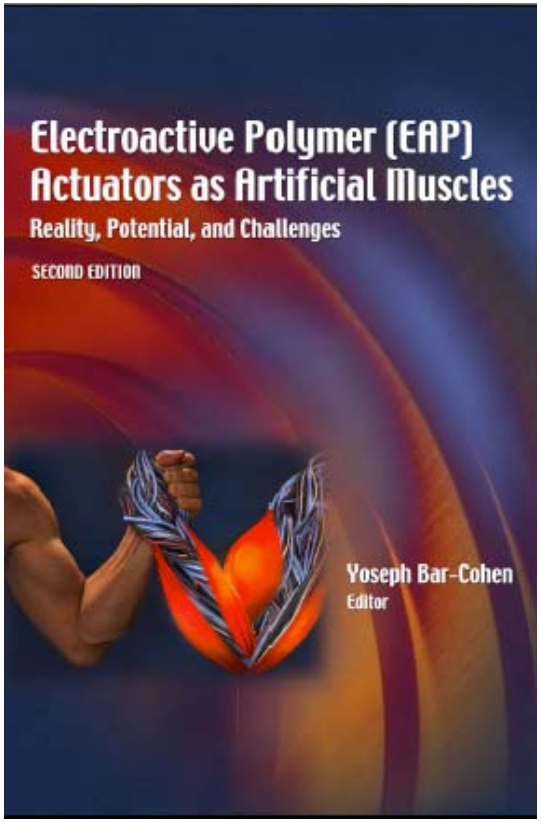
EDITED BY
Yoseph Bar-Cohen

Taylor & Francis

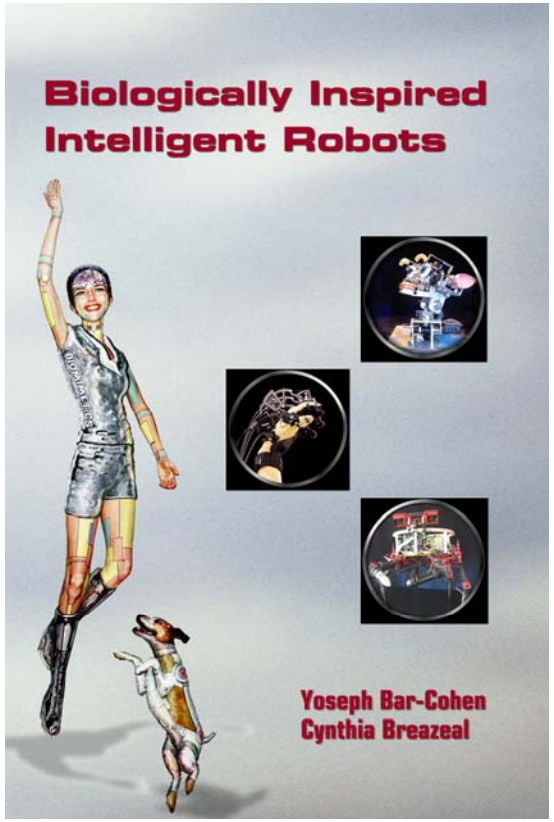
Book chapters

Chapter	Author(s)
1. Introduction to Biomimetics: The wealth of inventions in Nature as an inspiration for humans innovation	Y. Bar-Cohen, JPL
2. Biological Mechanisms as Models for Mimicking -	Kenneth Meijer, Universiteit Maastricht, The Netherlands , Juan C Moreno and Hans C.M.S Savelberg
3. Mechanization of Cognition	Robert Hecht-Nielsen, UC, San Diego,
4. Evolutionary Robotics and Open-Ended Design Automation	Hod Lipson, Cornell U.
5. Genetic Algorithms: Mimicking Evolution and Natural Selection in Optimization Models	Tammy Drezner and Zvi Drezner, CSU, Fullerton
6. Mobility, Manipulation and Robotic Mechanisms	David Hanson, UT at Dallas and Human Emulation Robotics, LLC
7. Bionanorobotics - A Field Inspired by Natures	A. Ummat[1], A. Dubey[1,2], and C. Mavroidis [1]Northeastern University, Boston, MA, [2]Department of Biomedical Engineering, Rutgers University, NJ
8. Molecular Design of Biological and Nano-Materials	Shuguang Zhang, Hidenori Yokoi and Xiaojun Zhao, MIT
9. Muscle-based actuator systems in bio-hybrid devices	Robert G. Dennis, Dr. of Mechanical Eng., University of Michigan; and Hugh Herr, MIT
10. Artificial muscles using Electroactive Polymers (EAP)	Yoseph Bar-Cohen, JPL
11. Biological Inspired Optical Systems	Robert Szema and Luke P. Lee, Bioengineering, UC Berkeley, CA
12. Multifunctional Materials	Sia Nemat-Nasser, Syrus Nemat-Nasser, Thomas Plaisted, Anthony Starr, and Alireza Vakil-Amirkhizi, University of California, San Diego (UCSD)
13. Defense and attack strategies and mechanisms in biology	Julian FV Vincent, The University Bath, England
14. Biological Materials in Engineering Mechanisms	Justin Carlson, Shail Ghaey, Sean Moran, Cam Anh Tran, David L. Kaplan, Tufts University, Medford, MA
15. Functional surfaces in biology - mechanisms and applications	Stanislav N. Gorb, MPI for Metals Research, Stuttgart, Germany
16. Biomimetic and biologically inspired control	Zhi-Wei, Lou and Shigeyuki Hosoe, and Ito Bio-Mimetic Control (BMC) Research Center, RIKEN, Aichi, Japan
17. Interfacing Microelectronics and the Human Body	Mark Humayun, James Weiland, Raj (Rajad) Agrawal USC, Los Angeles, CA; Gianluca Lazzi, and Keyoor Gosalia North Carolina State University
18. Artificial support and replacement of human organs	Pramod Bonde, JHU, Baltimore, MD
19. Nastic structures – the enacting and mimicking of plant movements	Rainer Stahlberg and Minoru Taya, University of Washington, Seattle WA
20. iomimetics - Reality, Challenges, and Outlook	Y. Bar-Cohen, JPL

Related books



1st Edition (March, 2001)
2nd Edition (March, 2004)



May, 2003

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

Other References

Proceedings

SPIE - Y. Bar-Cohen (Editor), Proceedings of the SPIE's ElectroActive Polymer Actuators and Devices (EAPAD) Annual Conference, Annual International Symposium on Smart Structures and Materials (SSM)

- 6th Symposium on SSM, Vol. 3669, ISBN 0-8194-3143-5, (1999), pp. 1-414
- 7th Symp. on SSM, Vol. 3987, ISBN 0-8194-3605-4 (2000), pp 1-360.
- 8th Symp. on SSM, , Vol. 4329, ISBN 0-8194-4015-9 (2001), pp. 1-524.
- 9th Symp. on SSM, , Vol. 4695, ISBN 0-8194-4443-X (2002). pp. 1-506.
- 10th Symp. on SSM, , Vol. 5051, ISBN 0-8194-4856-7 (2003), pp. 1-556.
- 11th Symp. on SSM, , Vol. 5385, ISBN 0-8194-5302-1 (2004) , pp. 1-572.
- 12th Symp. on SSM, , Vol. 5759, ISBN 0-8194-5740-X, (2005) pp. 1-550.

MRS

- Q.M. Zhang, T. Furukawa, Y. Bar-Cohen, and J. Scheinbeim (Eds), "Electroactive Polymers (EAP)," ISBN 1-55899-508-0, 1999 MRS Symposium Proceedings, Vol. 600, Warrendale, PA, (2001), pp 1-336.
- Y. Bar-Cohen, Q.M. Zhang, E. Fukada, S. Bauer, D. B. Chrisey, and S. C. Danorth (Eds), "Electroactive Polymers (EAP) and Rapid Prototyping," ISBN 1-55899-634-6, 2001 MRS Symposium Proceedings, Vol. 698, Warrendale, PA, (2002), pp 1-359.

Websites

- WW-EAP Webhub: **http://eap.jpl.nasa.gov/**

WW-EAP Newsletter

- **http://ndeaa.jpl.nasa.gov/nasa-nde/lommas/eap/WW-EAP-Newsletter.html**

Course schedule

08.30-09:00	Introduction - why mimic nature?
09:00-10:30	Nature's inventions as an inspiring model for biomimetics
Break	
10:45-11:30	Technology of artificial nature (including artificial organs, artificial materials, and artificial muscles)
11:30-12:00	Mechanical engineering in nature and related technologies (including mechanisms, structures, parts, defense and attack tools, and mobility techniques)
Lunch	
01:00-01:30	Mechanical engineering in nature and related technologies (including nastic structures, nano to mega scaling issues, manipulators and mechanical devices)
01:30-02:30	Mimicking natures' materials and processes (including multifunctional materials, silks, just in time fabrication, materials as integrated systems, and ink-printing for rapid 3D prototyping)
02:30-03:00	Current and potential applications (including bio-sensors, haptics, human/machine interfaces and user friendly systems)
Break	
03:15-04:00	Current and potential applications (including robotics, organic systems using electrically conducting polymers, MEMS, and nanotechnology)
04:00-04:30	Open discussion
04:30-05:00	Summary and expectations for the future of biomimetics

Why mimic nature?

The animals during the tsunami run while leaving the people behind

Swallows can hang themselves comfortably on a stucco wall

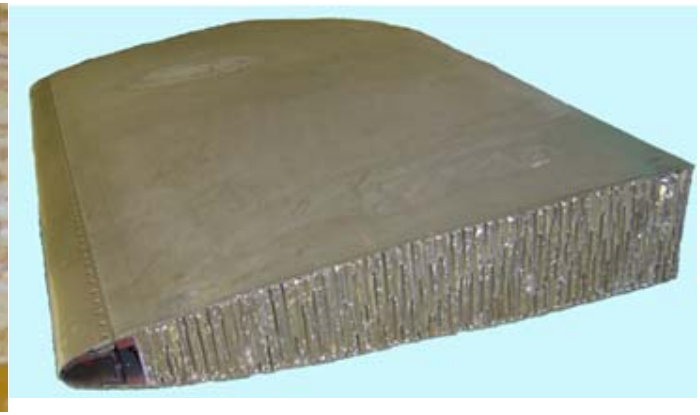
The woodpecker does not get dizzy after strong tapping on wood

[Courtesy of Ulf T. Runesson, Faculty of Forestry and the Forest Environment, Lakehead University, Ontario, Canada: www.borealforest.org]

Numerous examples from nature

- Humans can conduct a comprehensive conversation at a highly noisy environment
- To get food, the penguins female and male leave each other at different periods of the cold winter in Antarctica and upon returning they quickly find their mate from voice and face recognition in a crowd of hundreds of their peers. This is done in spite of the noise from the others.
  - There is no equivalent sound receiver that can be used to interpret signals with a poor signal to noise ratio
- Ants are able to find tiny amounts of food leftovers
  - This capability can inspire a novel homeland defense miniature robots that would continuously search for explosives and other terrorists related hazards
    - Upon finding, the miniature robots can gather around the finding and send information about the site and the activity. Then, once they reach a critical mass they can detonate themselves to eliminate the threat.

Biology – inspirating human innovation

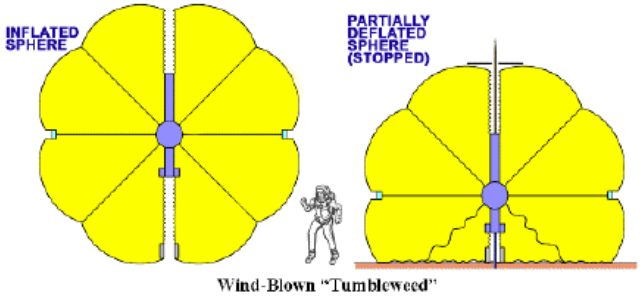


The honeycomb is now part of almost every aircraft

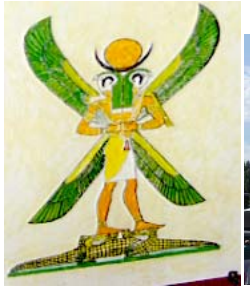
The spider is quite an “engineer”. Its web may have inspired the fishing net, fibers, clothing and others.

Shelled creatures inspired human body defense armors

Nature as a model for engineering



The tumbleweed as an inspiring structure



Human vision and reality of flying

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/

Multiple locomotion capabilities

Inspiring multi-tasking using scalable autonomous robot colonies

Flying, walking, swimming & diving

Hopping, flying, crawling & digging

Coordinated robotics

Neural networks & expert systems

Models for Robots with flexible actuators

Nastic structures – the mimicking of plants

Venus Flytrap *(Dionaea Muscipula)*

Sensitive Fern (*onoclea sensibilis*)

Picher plant (*Sarracenia purpurea*)

Nastic structures – the enacting and mimicking of plant movements (Ch. 19)

Rainer Stahlberg and Minoru Taya, University of Washington, Seattle WA

- Plants are adaptive machines that have developed and perfected their structures over millions of years of evolution in constantly changing and increasingly complex environments.
- With their autonomous and locally controlled responses plant movements do not require remote control through a central nervous system or computer.
  - Nastic structures as well as their motors are optimized to use the potentialities of solvent.
  - A striking particularity of nastic structures is an efficient and inconspicuous design that integrates two or more functions (like motor and valve or sensor, motor and lever) in one smoothly operating unit.
- The knowledge gained from studying nastic structures is key input for designing human-made adaptive structures and smart materials and includes novel and increasingly complex multifunctional materials like fiber-reinforced bio-composites, pressure-sensing, humidity-sensing, sugar (or other chemical)-sensing fiber-reinforced hydrogels, nastic-inspired combinations of actuators and force-guiding structures like matrixes with pressurized body inclusions as well as arrayed actuators combining memory shape alloys, photomechanical films, electro-active polymers and sensing hydrogels in one multifunctional unit.
- In the past, some passive plant structures have served as the basis for a few successful phytomimetic designs of buildings (Paxton's Crystal Palace in London following rib construction of floating leaves from *Victoria amazonica*), attachments (Velcro fastener after burdock or *Arctium* seed pods) and airplanes (wings of glider and motor planes with extremely reduced stalling features were designed after *Zanonia* seeds).
- Powerful and energy-efficient, auto-sensing and autonomously adjusting, multifunctional, exhaust-free and silent actuators, tools, motors as well as new materials from leak-free storage of liquids to the silent demolition of buildings can be based on the integrated workings of nastic structures.
- By reviewing the major guiding principles and selected examples of natural nastic structures, this chapter is meant to inspire, stimulate and broaden their current and future technical application.

What does nature offer as a model?

- Nature is filled with lasting solutions that use minimal resources to perform at maximum.
- Nature's inventions have led to effective algorithms, methods, materials, processes, structures, tools, mechanisms, and systems.
- There are numerous examples of biomimetic successes including some that are simple copies of nature, such as the use of fins for swimming.
- Others examples were inspired by biological capabilities with greater complexity including the mastery of flying that became possible only after the principles of aerodynamics were better understood.
- Some commercial implementations of biomimetics can be readily found in toy stores, where robotic toys are increasingly appearing and behaving like living creatures.
- More substantial benefits of biomimetics include the development of prosthetics that closely mimic real limbs as well as sensory-enhancing microchips that are being used to interface with the brain to assist in hearing, seeing, and controlling instruments.
- In this course, various aspects of the field of biomimetics will be reviewed, examples of inspiring biological models and practical applications of biomimetics will be described, and challenges and potential directions of the field will be discussed.

Reality in biology but science fiction in technology

- Imagine a smart microchip that is buried in the ground for a long time.
- Upon certain triggering conditions this chip begins to grow.
- It consumes materials from its surroundings, converting them into energy and structural cells.
- In turn, the chip grows further and reconfigures its shape to become a mobile robot.
- Using its formed mobility, the chip becomes capable of searching and locating critical resources consuming them to grow even more.
- The type and function of the specific cells that are formed depends on their role in the growing structure.
- This science fiction scenario is inspired by true-life biology of the growth of chicks from an egg or plants from a seed.
- Yet given all our technological advances, it is still impossible to engineer such a reality.

2. Nature's inventions as an inspiring model for biomimetics

Biomimetics

Biologically Inspired Technologies

Yoseph Bar-Cohen, JPL

Nature as the world largest experimental lab

- Through evolution, nature has “experimented” in its “lab” on the world with various solutions to its challenges and has improved the successful solutions.
- The surviving organisms that nature created are not necessarily optimal for their performance. Effectively, all they need to do is to survive long enough to reproduce.
- Living systems archive the evolved and accumulated information by coding it into the species’ genes and passing the information from generation to generation through self replication.
- Through evolution nature, or biology, has experimented with the principles of physics, chemistry, mechanical engineering, materials science, mobility, control, sensors, and many other fields that we recognize as science and engineering.
- The process has also involved scaling from nano, as in the case of bacteria and virus, to the macro and mega, including our life scale and the dinosaurs, respectively.
  - While there is still doubt regarding the reason why creatures such as the mammoth went extinct, one may argue that the evolutionary experiment with mega-scale terrestrial biology failed. These creatures can now be found only in excavation sites and natural history museums.
  - In contrast, mega-scale marine creatures such as the whales did survive so far.

Nature as an inspiring model

- Nature has always served as a model for mimicking and inspiration to humans in their desire to improve their life.
- By adapting mechanisms and capabilities from nature, scientific approaches have helped humans understand the related phenomena and the associated principles in order to engineer novel devices and improve their capability.
- The cell-based structure, which makes up the majority of biological creatures, offers the ability to grow with fault-tolerance and self repair, while doing all of the things that are characterizing biological systems.
- Biomimetic structures that are made of multiple cells would allow for the design of devices and mechanisms that are impossible with today's capabilities.
- Emerging nano-technologies are increasingly enabling the potential of such capabilities.

Bio imitation and inspiration

- Biology offers a great model for imitation, copying and learning, and inspiration for new technologies.
  - The design and function of fins, which divers use, was copied from the legs of water creatures like the seal, goose and frog.
  - In contrast, flying was inspired by birds using human developed capabilities

- The distinction between technologies resulting from various adaptation approaches is not always clear.
  - In the case of studying photosynthesis in a leaf, some may argue that the invention of the solar cell is an *imitation*, while others may see it as a biologically *inspired* technology.
    - While both cases use sunlight as a source of energy, they do not perform the same process nor create the same output.

Evolution led to various solutions

Copying nature

Diving fines were copied from the gossamer structure of the foot of swimming animals and birds and they provide significantly enhancement of humans’ swimming and diving

Inspiration of nature

The desired to fly was implemented using aerodynamic principles leading to enormous capabilities

Synthetic life

- Advances in understanding and unraveling the genetic code and the ability to manipulate and splice genes have made the possibility of creating synthetic life an increasing reality.

- Biologist are now able to engineer bacteria and develop drugs that otherwise must be extracted from rare plants at a very high cost.
  - Bacteria and yeast are produced to build proteins with synthetic amino acids having novel properties that are impossible to find in nature.

- Researchers are also working on assembling simple cells from basic components with an ability that is much broader than recombining DNA.

- The possibility of synthetically producing living cells from scratch are increasingly become a near future potential.

Artificial Life

- The name Artificial Life (A-Life) suggests the synthesizing of life from non-living components.

- A-Life is a technical field that is dedicated to the investigation of scientific, engineering, philosophical, and social issues involved in our rapidly increasing technological capability to synthesize from scratch life-like behaviors using computers, machines, molecules, and other alternative media.

- Artificial Life focuses on the broad characteristics of biology and contributes to the development of machines that evolve, sociable robots, artificial immune systems that protect computers from malicious viruses, and virtual creatures that learn, breed, age, and die.

- Biologists can now study evolution in virtual worlds, and medical students and doctors can study the operation mechanisms of various living organs (including the heart with its cells) enabling to learn in ways that are impossible to do with actual living organs.

Artificial Intelligence (AI)

- According to the American Association for Artificial Intelligence (AAAI), artificial intelligence (AI) is, “the scientific understanding of the mechanisms underlying thought and intelligent behavior and their embodiment in machines”.
- AI is a branch of computer science that studies the computational requirements for such tasks as perception, reasoning, and learning, to allow development of systems that perform these capabilities.
- AI researchers are addressing a wide range of problems that include studying the requirements for expert performance of specialized tasks, explaining behaviors in terms of low-level processes, using models inspired by the computation of the brain and explaining them in terms of higher-level psychological constructs such as plans and goals.
- The field seeks to advance the understanding of human cognition, understand the requirements for intelligence in general, and develop artifacts such as intelligent devices, autonomous agents, and systems that cooperate with humans to enhance their abilities.
- The name AI was coined in 1956, though the roots of the field may be attributed to the efforts in World War II to crack enemy codes by capturing human intelligence in a machine that was called Enigma.
  - This approach eventually led to the 1997 computer success of IBM’s Deep Blue in beating the world-champion chess player Garry Kasparov.
  - Even though this was an enormous success for computers, still it does not resemble the human intelligence.
- AI technologies consist of an increasing number of tools, including artificial neural networks, expert systems, fuzzy logic, and genetic algorithms.

Mechanization of cognition (Chapter 3)

Robert Hecht-Nielsen, UC, San Diego, Califonia

- In mechanization of cognition (the act or process of knowing including both awareness and judgment) one needs to understand its fundamentals. Generally, there are two fundamental processes of cognitive knowledge acquisition – *training* and *education*.
  - Key components of cognition include language, sound, and vision.
- Human (and higher mammal) intelligence involves a number of strongly interacting, but functionally distinct, brain structures.
- Of these, significant progress has now been made on three:
  - Cerebral cortex and thalamus: This is the *engine of cognition* (and the focus of this Chapter),
  - Basal ganglia: The *behavioral manager* of the brain, which manages action evaluation, action selection, and skill learning
  - Cerebellum: The *autopilot* of the brain, which implements detailed control of routine movement and thought processes with little or no need for ongoing cognitive involvement once a process has been launched and until it needs to be terminated.
- There are a number of other, smaller-scale, brain functions that are also critical for intelligence (e.g., ongoing drive and goal state determination by the limbic system), but these are not discussed in this chapter.
- Of all of the components of intelligence, cognition is, by far, the most important. It is also the one that has, until now, completely resisted explanation and this Chapter provides the first sketch of how cognition can be mechanized.
- The approach is based on the author's theory of vertebrate cognition, which is described in the Chapter's Appendix.
- This Chapter is not an historical description of 'how cognition was mechanized;' but is instead an 'initial plan for mechanizing cognition.'
- Initial progress in implementing this plan in areas such as language and hearing has been encouraging.

Evolutionary Robotics and Open-Ended Design Automation (Chapter 4)

Hod Lipson, Cornell U.

- The process of successive adaptation by improvement and recombination of basic building blocks is evolutionary in its nature.
- Unlike classical genetic algorithms, which is open ended, we do not know a-priory what components we will need and how many of them.
- The permutation space is exponential, and complexity is unbounded.
- This is perhaps a subtle but key difference between optimization, and synthesis.
  - In optimization problems we tune the values of a set of parameters in order to maximize a target function. The set of parameters, their meaning and their ranges are predetermined.
  - Synthesis, on the other hand, is an open-ended process where we can add more and more components, possibly each with their own set of parameters.
- Consider for example a case where we need to design a new electronic circuit that performs some target function.
  - One approach would be to manually provide a basic layout of resistors, capacitors, and coils, and then try to automatically tweak their values so as to maximize performance.
  - Alternatively, we could start with a bucket of components, and use an algorithm to automatically compose them into a circuit that performs the target function.
  - The former case would be optimization, and the later would be an example of synthesis.
- There are numerous examples and many books dedicated to the application of evolutionary optimization in almost any engineering domain, but the use of evolution for open-ended design remains relatively unexplored, yet has the highest potential impact in its ability to ‘think outside the box’.

Genetic Algorithms: Mimicking Evolution and Natural Selection in Optimization Models (Chapter 5)

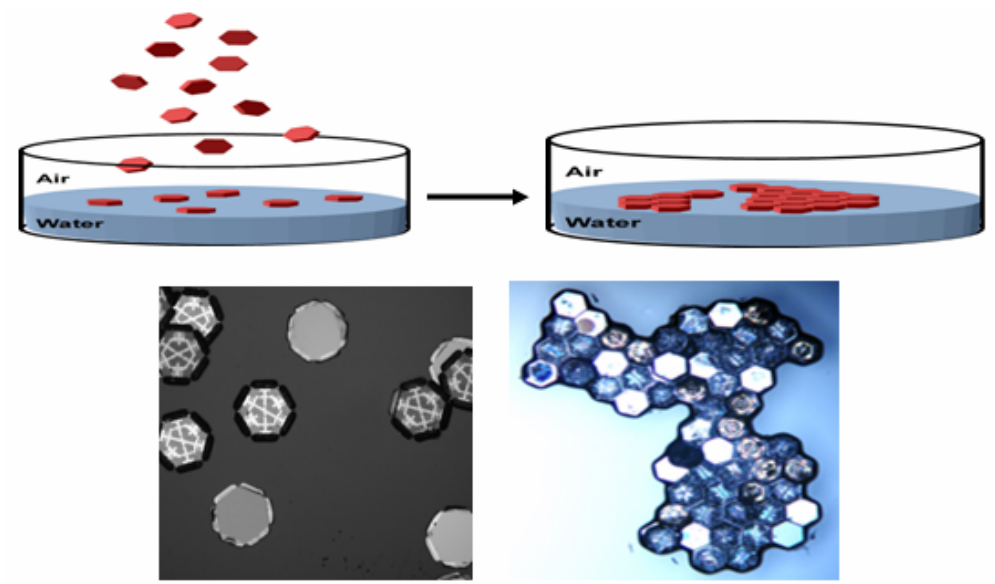
Tammy Drezner and Zvi Drezner, CSU, Fullerton

- Genetic algorithms mimic the principles of natural selection and the survival of the fittest.
- To survive, species must reproduce and regenerate and it requires new members of the population to be fit and adaptable to changing environmental conditions. Inherent to this theory is the definition of what constitutes the "fittest" that can change
  - The male bird of paradise in New Guinea is the fittest when his feathers and tail are very colorful and attractive to the female bird of paradise. The same colorful and beautiful male would not be the fittest in a different environment (off the island), one that is predator rich.
  - Similarly, the peppered moth, in England, during the Industrial Revolution would not have survived without a color adaptation. In urban areas, the fittest was the darker peppered moth that adapted to the new gray, ash-covered trees on which it rests. By blending into the tree, it protected itself from predators, while at the same time, in rural areas, the peppered moth continued to thrive and survive on lichen covered tree branches.
- Unlike nature, in genetic algorithms the definition of the "fittest" is stable. The more stable definition of "fittest" in genetic algorithms, in turn, allows for the ultimate achievement of an "ideal" population, a situation not paralleled in nature.
- In nature, species have to cope with invasion of other species and competetion for resources. Species diversity is rampant as genetic diversity is instrumental to adaptation. The survival of the fittest individual leads to survival of the species.
- In genetic algorithms, there is one species only. Occasionally generating offspring who are "fitter" than existing members in order to "enrich" the population "gene pool" incorporates invasion in genetic algorithms. Parallel genetic algorithms allow population movements, but those are of the same species. In compounded genetic algorithms, there is no population movement between the isolated populations.
- Offspring mutation is another natural selection tenet incorporated in genetic algorithms. Mutations occur quite frequently in nature. Most mutations are not beneficial to the species, while some, on rare occasions, are beneficial, are instrumental in adaptation, and, in fact, produce the "fittest" offspring. Some genetic algorithms incorporate mutations, some of which are beneficial.
- Other similarities consist of gender based traits and procedures for replacing and removing population members. In addition, nature allows for population or species growth and decline. These are occasionally practiced in genetic algorithms as well.
- This chapter demonstrates the superiority of the evolutionary process in solving analytical problems.

Nature as a model for structures and tools

Constructing structures from cells

Ch.1
FIGURE 4



Self-assembly of large numbers of Micro-Electro Mechanical System (MEMS) parts into two and three-dimensional arrays of engineered crystals

Biological Mechanisms as Models for Mimicking - Sarcomere Design, Arrangement and Muscle Function (Chapter 2)

Kenneth Meijer, Universiteit Eindhoven, Netherlands, Juan C Moreno, Consejo Superior de Investigaciones Científicas, Spain, and Hans H.C.M Savelberg Universiteit Maastricht, Netherlands

- In recent years, material scientists have developed polymer materials that can be used to develop artificial muscles.
- To facilitate robotic and prosthetic design such artificial muscles should be multi-functional, robust, modular and have the capacity to repair themselves in response to damage.
- It has been argued that studying the working principles of biological muscle may inspire the design of artificial muscles.
- This chapter gives an overview of the relationship between muscle form and function, with an emphasis on the sarcomeric design of muscle. The following issues are addressed
  1. muscles are multifunctional actuators,
  2. contractile proteins are organized in functional units called sarcomeres,
  3. muscle function is modified in two basic ways: a) modifying the sarcomere design and b) rearranging the sarcomeres
  4. muscle adaptation in response to functional demands. The chapter ends with a discussion on how the sarcomeric design of muscle can provide inspiration for the design of artificial muscles.

Engineered Muscle Actuators: Cells & Tissues (Ch. 9)

Robert G. Dennis, UNC Dept. of Biomedical Engineering, Hugh Herr, MIT Media Lab

- Muscle tissue as a mechanical actuator has great, though as-yet unrealized potential for use in engineered systems.
- Synthetic technologies such as electroactive polymers are rapidly emerging as quantitatively functional equivalents to muscle tissue, and it is likely that the technological evolution of EAP muscles will soon out-pace the natural functional evolution of living muscle tissue.
- This means that the quantitative performance advantages that muscle tissue has over some forms of synthetic actuators in terms of efficiency, power density and so forth are not likely to remain the case for very much longer.
- One then invariably must ask why it is advantageous to even consider the use of living muscle tissue as a mechanical actuator.
- It is easy to point out that the many disadvantages of muscle outweigh the few performance advantages it may have.
- The answer lies chiefly in the qualitative differences between muscle and competing synthetic actuator technologies, among these are those qualities that arise from muscle being a living tissue: its ability to functionally adapt and to potentially integrate seamlessly with other living structures.
- So it is likely that living muscle actuators will only be employed in practical systems where their qualitative advantages as living tissue can be exploited to maximum benefit, such as in hybrid biomechatronic prosthetic systems and implants, and perhaps in bioreactors where their biological products (such as edible proteins) are of primary importance.
- Certainly though, living muscle tissue serves as the explicit benchmark against which the performance of synthetic actuator technologies will be evaluated for many decades to come.

3. Technology of artificial nature

Biomimetics

Biologically Inspired Technologies

Yoseph Bar-Cohen, JPL

Artificial Organs

- It is increasingly common to augment body organs with artificial substitutes.
- This is the result of significant advances in materials that are bio-compatible, powerful electronics, and efficient miniature actuators.
- Artificial hands are designed to allow control of the fingers using a hand that matches the appearance of a human real hand.
- Artificial organs already include the heart, lung, kidney, liver, hip, and others.
- Smart limbs, known as Cyborgs, are increasingly being developed with various degrees of sophistication and operation similar to the biological model.
- The possibility of an artificial vision allowing a blind person to see is another growing reality.

Artificial support and replacement of human organs (Chapter 18)

Pramod Bonde, Johns Hopkins University School of Medicine

- The current emphasis on replacement by mechanical systems is already profoundly affected by newer technologies.
- In the future, bio-compatible surfaces will be designed keeping in mind the precise interactions at atomic and molecular levels rather than the trial and error approach that was adopted several decades ago.
- These newer technologies will definitely have an impact on future artificial medical implants, be it artificial heart valves, vascular conduits or artificial organ systems.
  - Design and technology will certainly move to center stage in the coming years.
  - Unique problems will be posed for the today's scientists, physicians and engineers, who are slow to adjust to collaborative research.
  - Current funding structure is limited in supporting such collaborations; the cost of such design and manufacturing is prohibitive for one group or individual organizations to sustain.
  - Answers to these problems will hopefully be addressed in the future federal funding mechanism as outlined in the initiative by NIH on nanotechnology.
- One of the questions that is frequently debated is whether future organ replacement technology will involve miniaturizing the current systems or building newer organ replacement systems from scratch.
- Miniaturization will certainly play an important role in devising therapeutic interventions such as drug delivery. However, current organ replacement systems have several disadvantages which will be difficult to overcome even if they are miniaturized.
- Devising organ replacement systems from scratch will help address the current problems of biocompatibility and better mimic the organ function at cellular level.
  - This will involve creating novel anatomical models of scaffoldings which are biocompatible and bioactive to allow cell growth and differentiation so that complex organs can be developed.
  - Such new organ systems will need to produce energy from oxygen, glucose and other substances freely available in the blood and be self-sufficient.
- As the pace of developments in the fields of nanotechnology, tissue engineering and others is accelerating, the reality of having a self sustaining artificial organ replacement system is a possible reality in the upcoming years.

EAP as Artificial Muscles (Chapter 10)

Y. Bar-Cohen, JPL

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

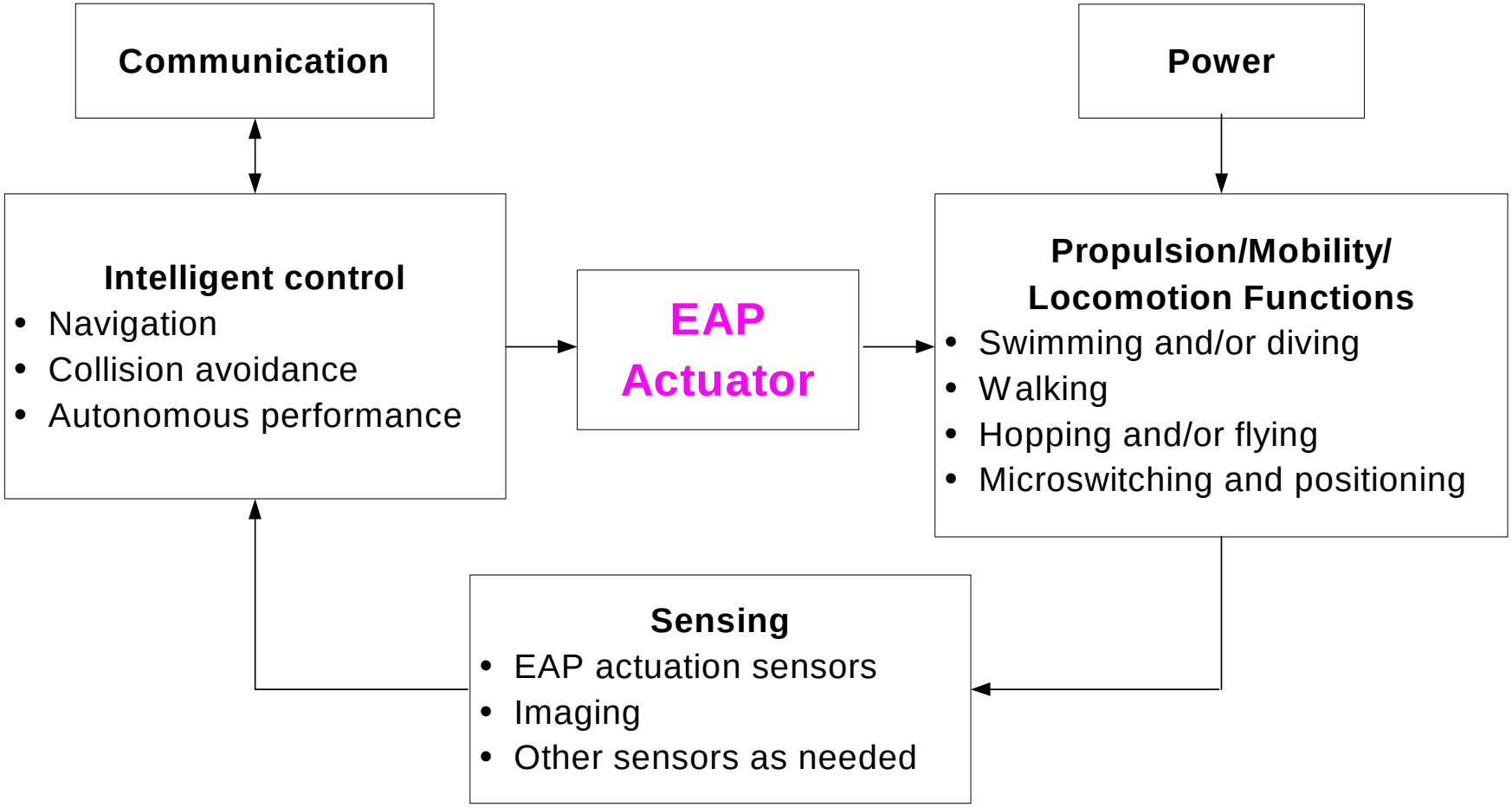
- Emulating biological muscles can enable various novel manipulation capabilities that are impossible today.

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

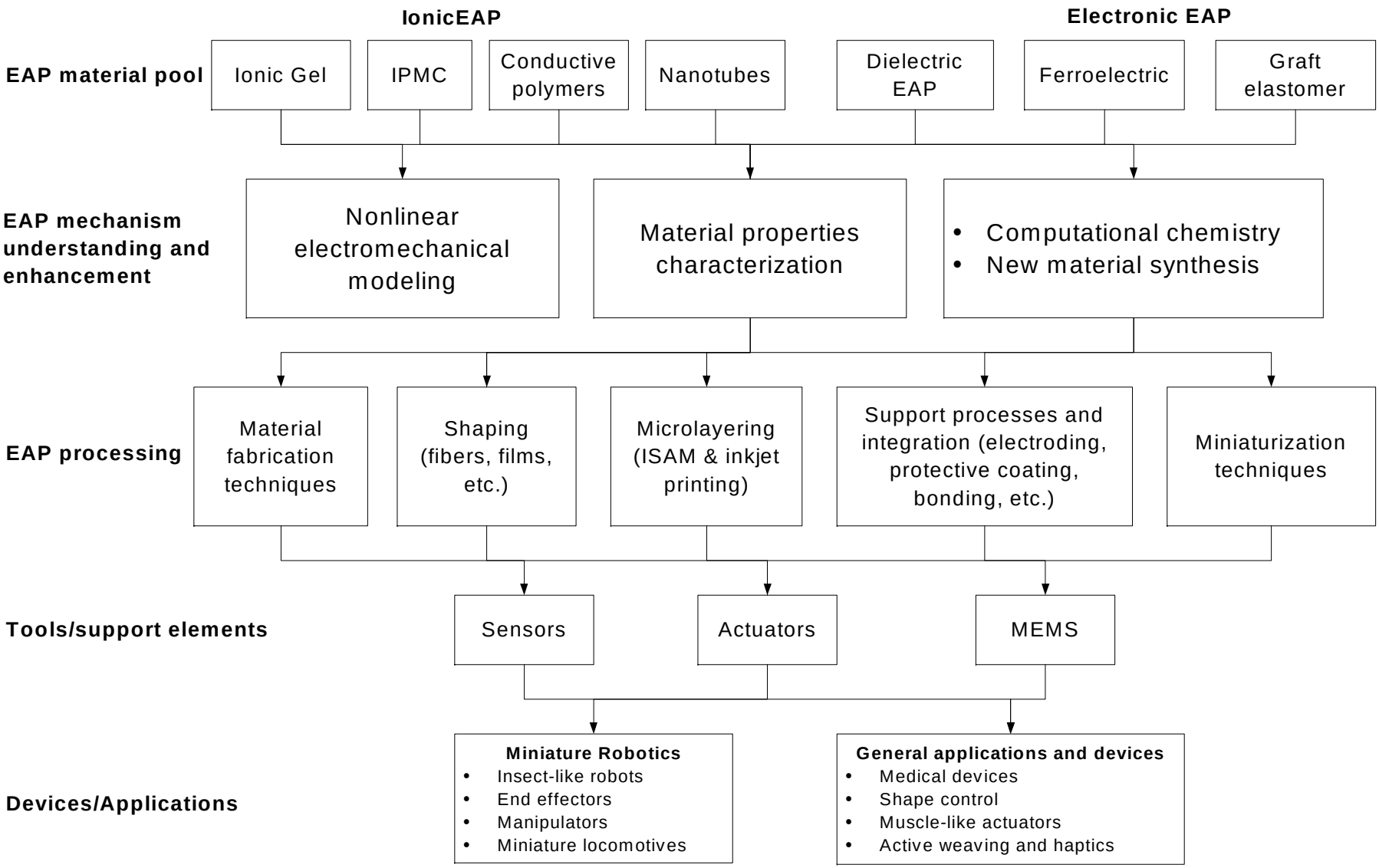
- EAP are resilient, fracture tolerant, noiseless actuators that can be made miniature, low mass, inexpensive and consume low power.

- EAP can potentially be used to construct 3-D systems, such as robotics, which can only be imagined as science fiction using such capabilities as inkjet printing.

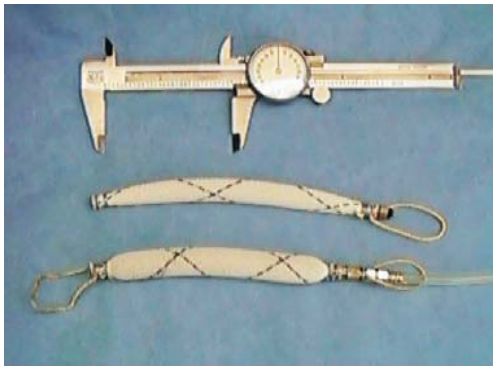
Elements of an EAP actuated robots



EAP infrastructure

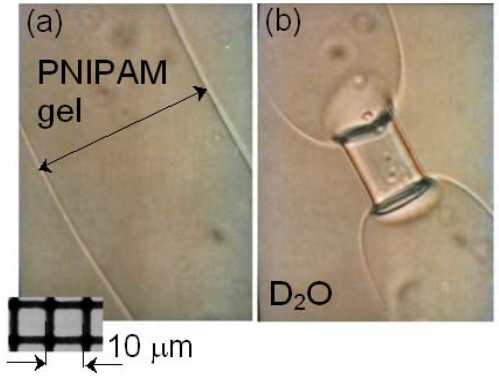


Non-electrical mechanically activated polymers



McKibben Artificial Muscles

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

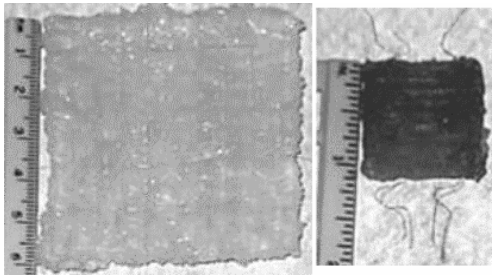


Laser Illuminated Polymer

Light activation (H. Misawa, Japan)

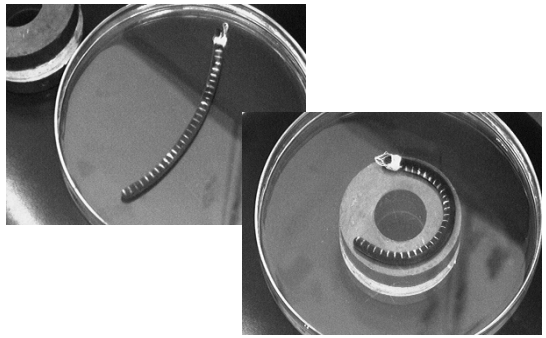
Shape Memory Polymers

Heat/pressure activation (W. Sokolowski, JPL)



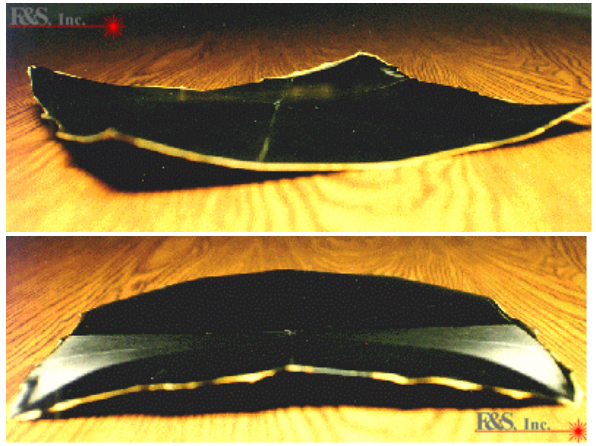
Ionic Gel Polymers

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

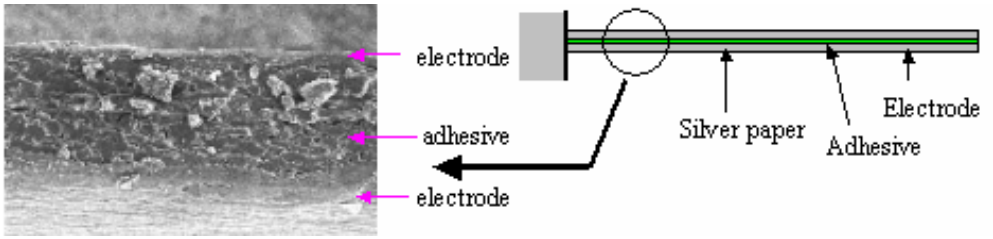
- Dielectric EAP
- Electrostrictive Graft Elastomers
- Electrostrictive Paper
- Electro-Viscoelastic Elastomers
- Ferroelectric Polymers
- Liquid Crystal Elastomers (LCE)

IONIC EAP

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

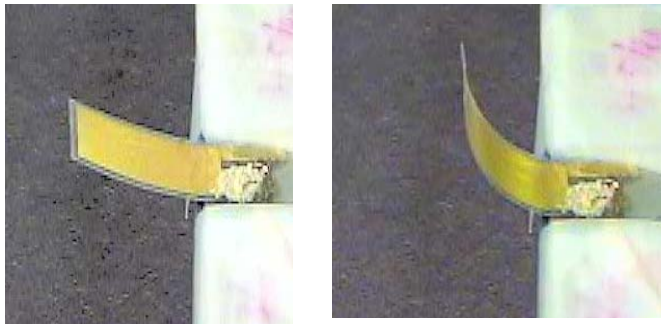
Electronic EAP

ELECTRIC FIELD OR COULOMB FORCES DRIVEN ACTUATORS



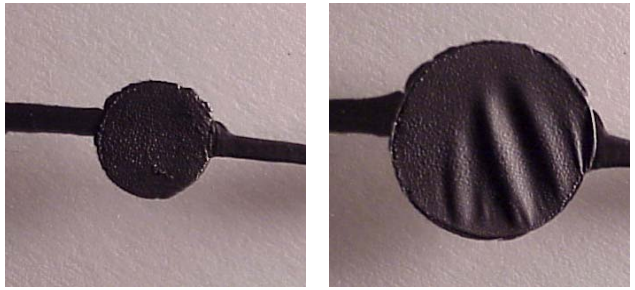
Paper EAP

[J. Kim, Inha University, Korea]



Ferroelectric

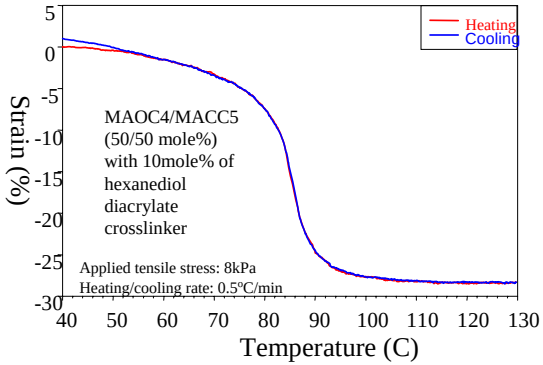
[Q. Zhang, Penn State U.]



Voltage Off **Voltage On**

Dielectric EAP

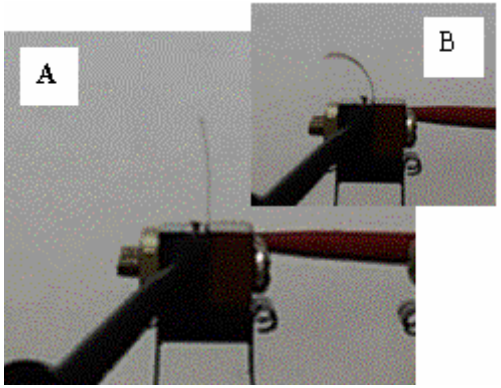
[R. Kornbluh, et al., SRI International]



Liquid crystals

(Piezoelectric and thermo-mechanic)

[B. R. Ratna, NRL]

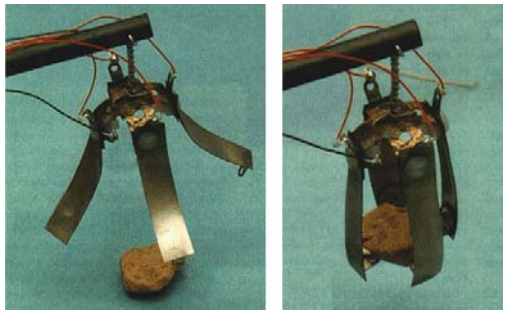


Graft Elastomer

[J. Su, NASA LaRC]

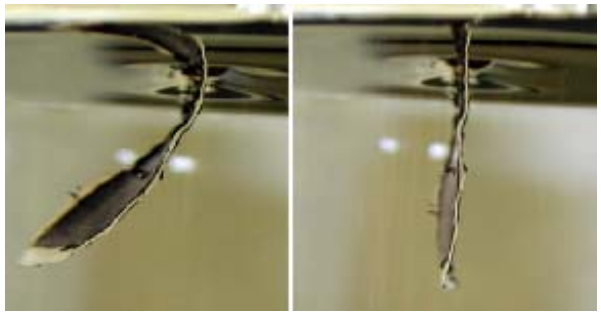
Ionic EAP

Turning chemistry to actuation



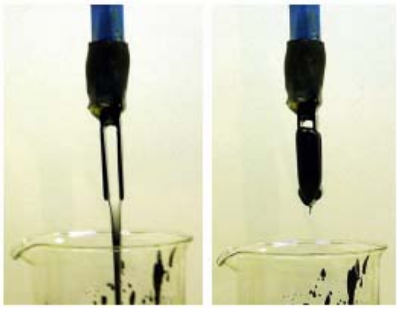
IPMC

[JPL using ONRI, Japan & UNM materials]



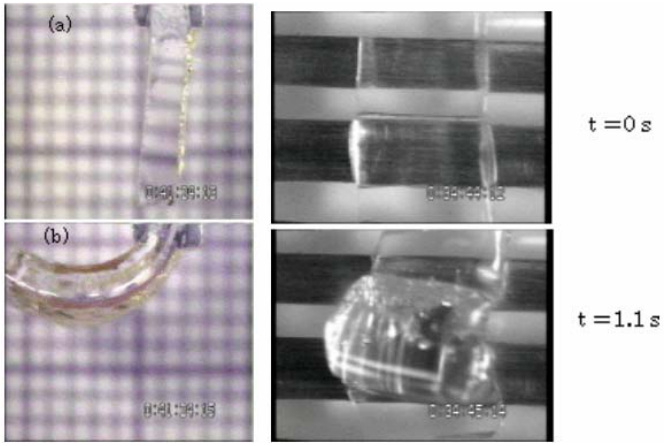
Conductive Polymers

[Made and photographed at JPL]



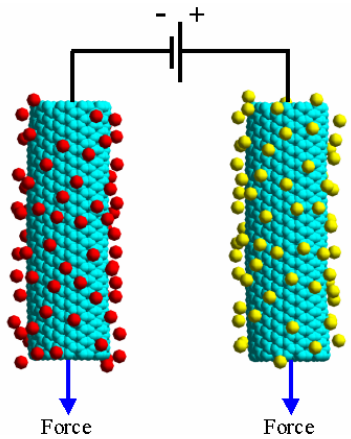
ElectroRheological Fluids (ERF)

[ER Fluids Developments Ltd]



Ionic Gel

[T. Hirai, Shinshu University, Japan]



Carbon-Nanotubes

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

Comparison between EAP and widely used transducing actuators

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

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

Current EAP
Advantages and disadvantages

EAP type	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.

Applications

Underway or under consideration

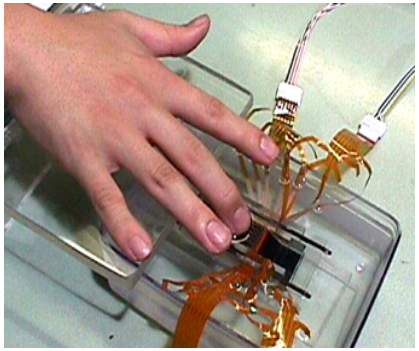
- **Mechanisms**
  - Lenses with controlled configuration
  - Mechanical Lock
  - Noise reduction
  - Flight control surfaces/Jet flow control
  - Anti G-Suit
- **Robotics, Toys and Animatronics**
  - Biologically-inspired Robots
  - Toys and Animatronics
- **Human-Machine Interfaces**
  - Haptic interfaces
  - 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**

Human-Machine Interfaces

- Interfacing human and machine to complement or substitute our senses would enable important medical applications.

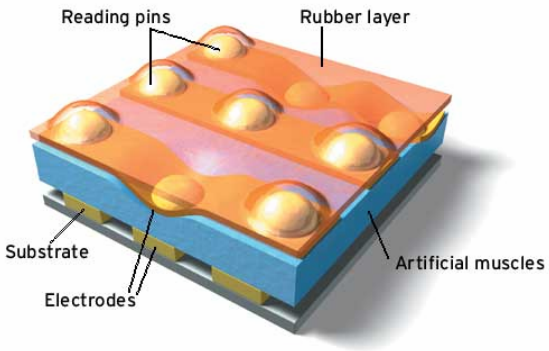
- Researchers at Duke U. connected electrodes to a brain of a monkey and were able to control a robotic arm. This breakthrough opens the possibility that the human brain would be able to operate prosthetics that are driven by EAP.

- 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)

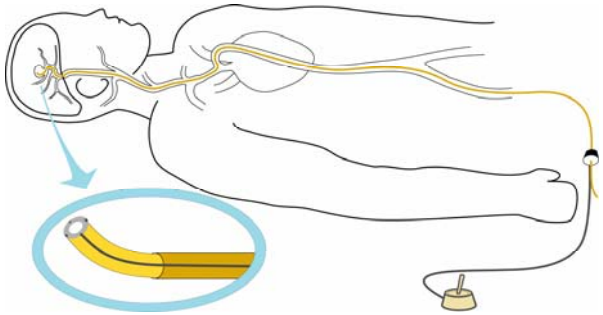


Active Braille Display

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

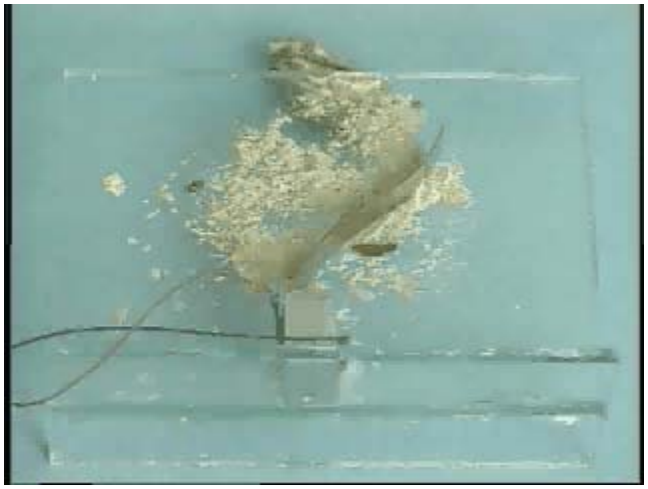
An EAP Braille display being tested by a blind person

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
- Interfacing Neuron to Electronic Devices Using EAP
- Active Bandage

Exploration of planetary applications

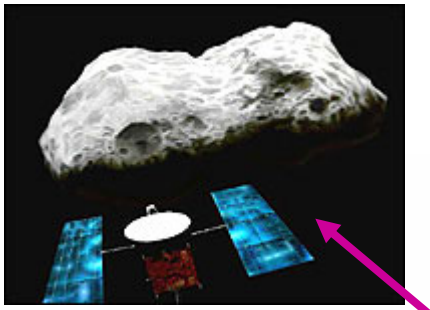
Dust wiper



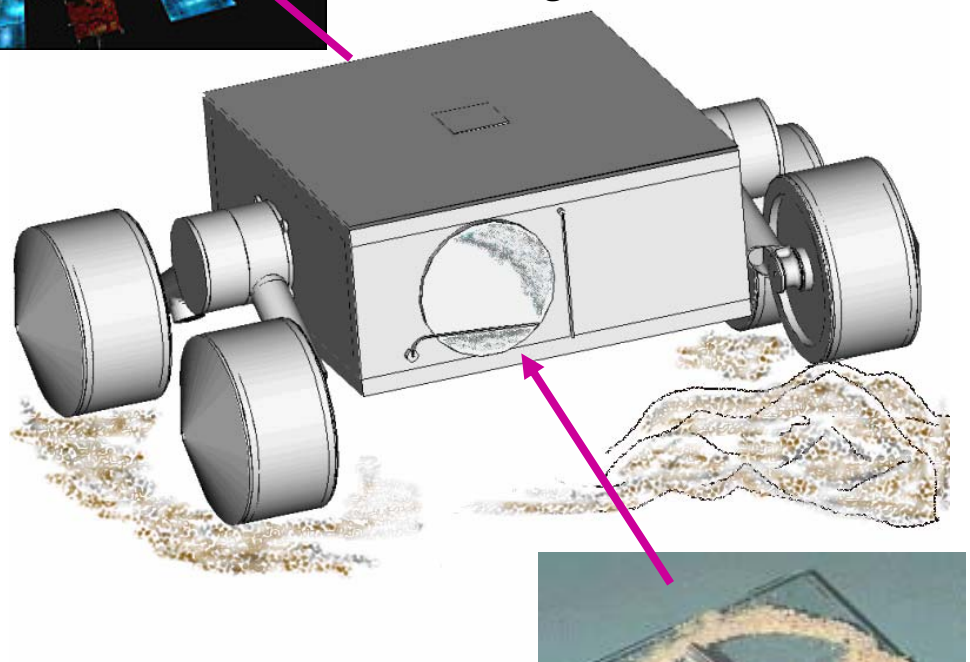
Sample handling robotics

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.

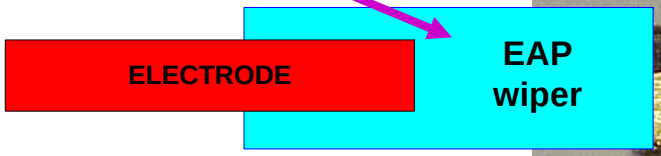


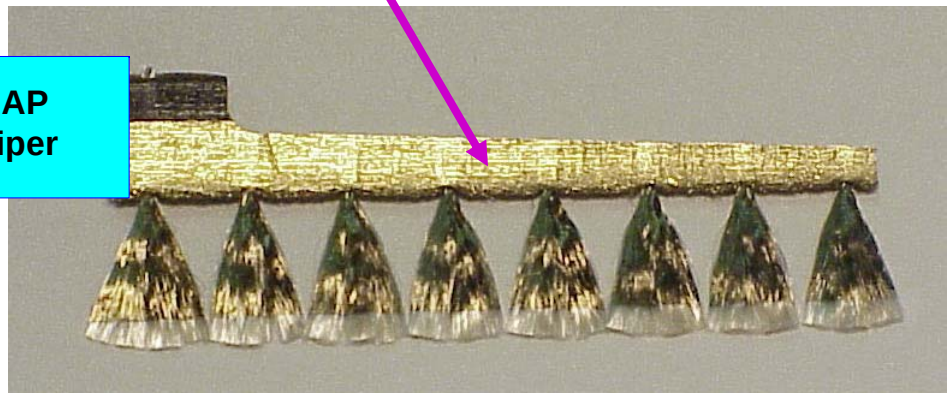
- An IPMC actuated wiper was selected as a baseline for the dust removal from the visual/IR window.
- The technical challenges were beyond the technology readiness requirements

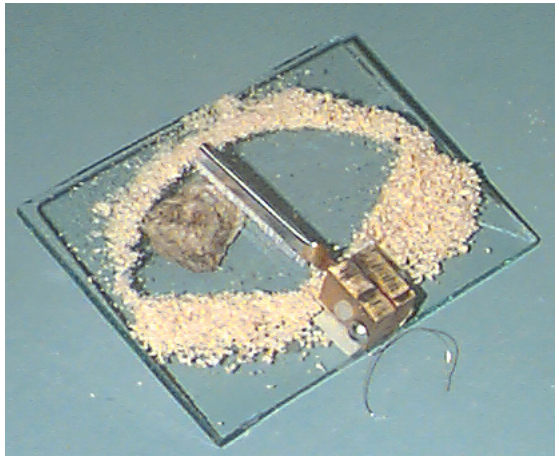
Dust wiper activated by EAP using wiper blade attachment

Actuated by 1-3 volts

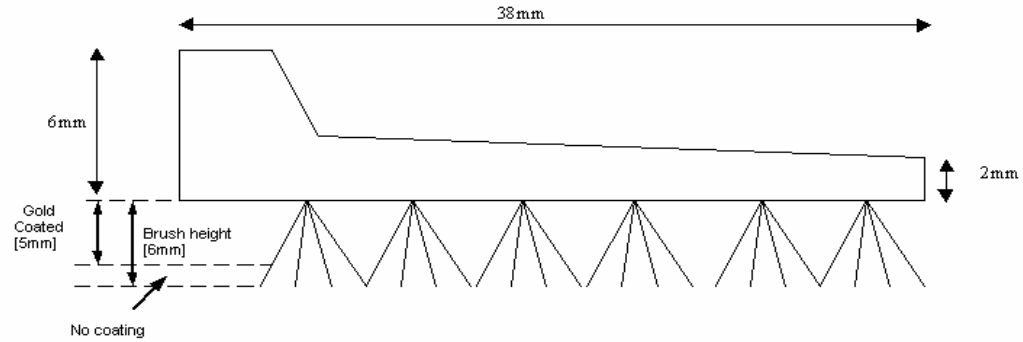
Biased with 1-2KV for dust repulsion







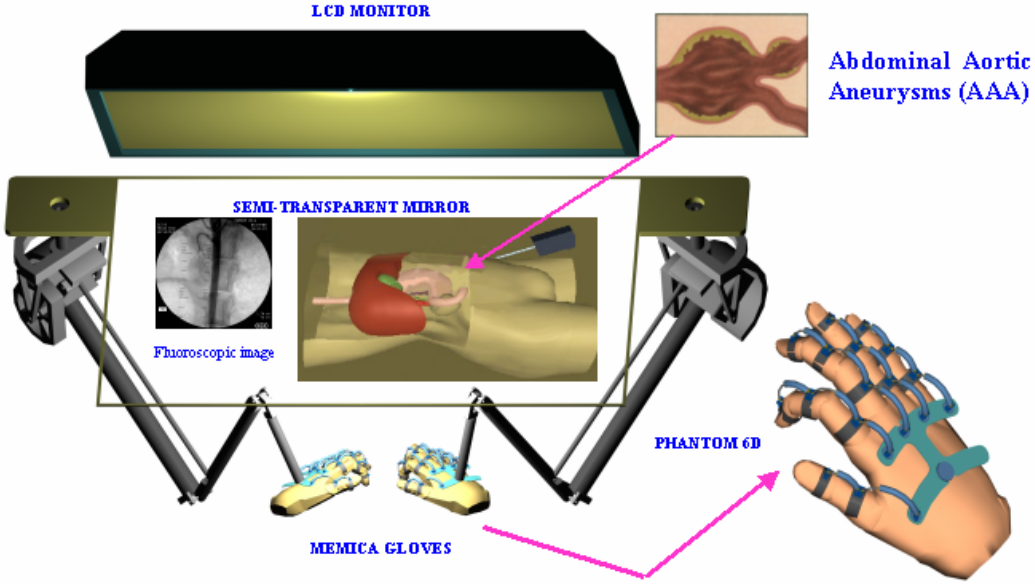
Graphite/Epoxy wiper blade* with fiberglass brush coated with gold

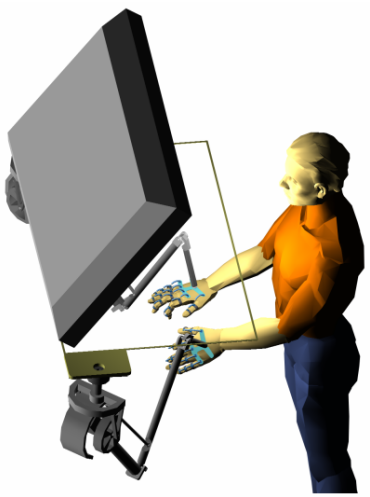


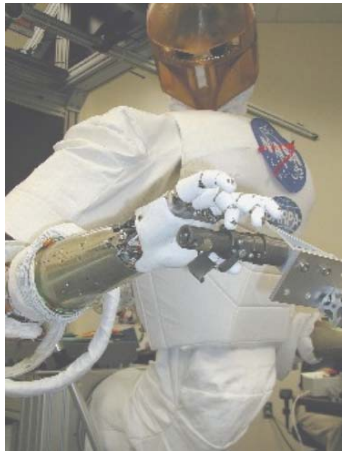
* Made by Energy Science Laboratories, Inc., San Diego, California

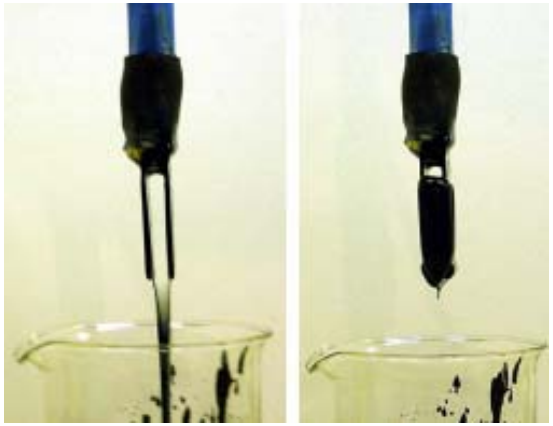
MEMICA*

(MEchanical MIrroring using Controlled stiffness and Actuators)

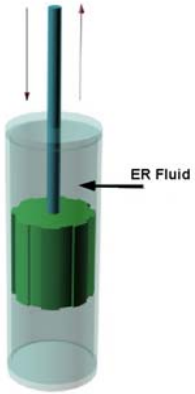


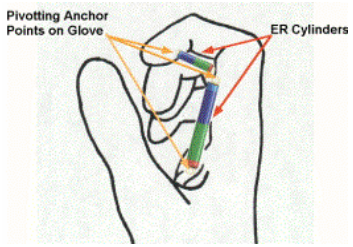






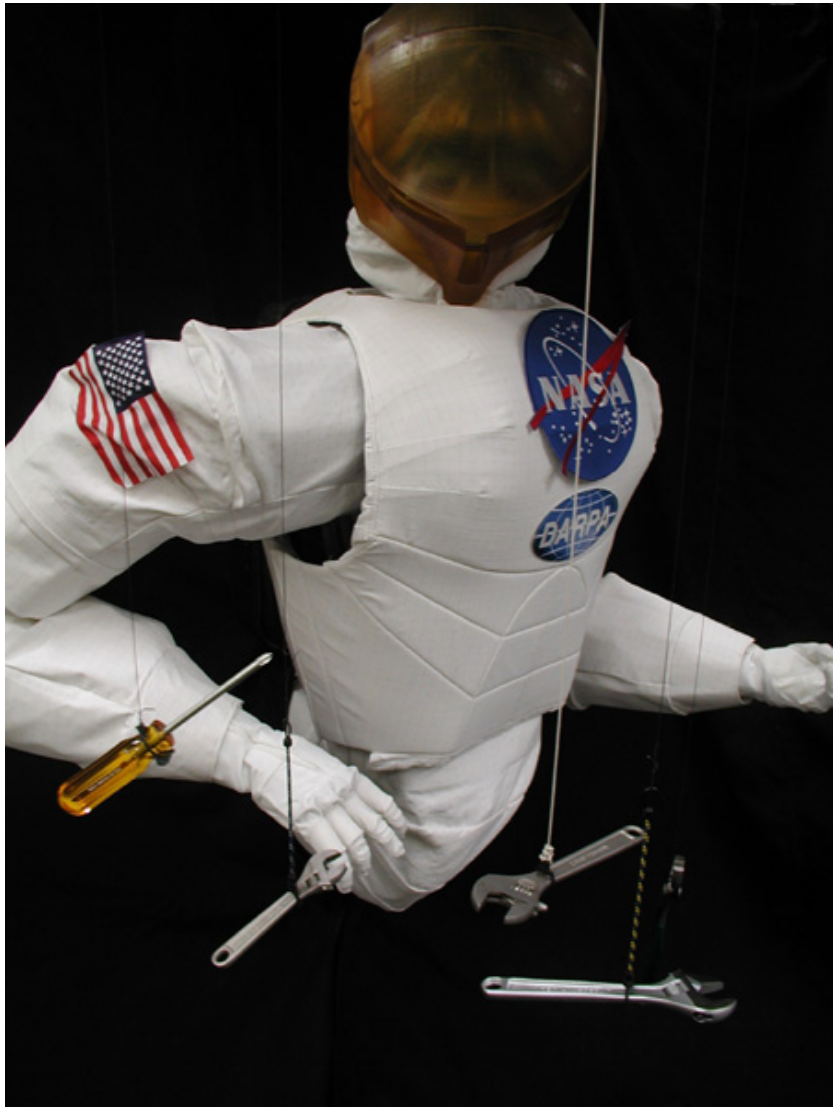
Electro-Rheological Fluid at reference (left) and activated states (right). [Smart Technology Ltd, UK]





* Joint with C. Mavroidis, formerly Rutgers U.

Robonaut

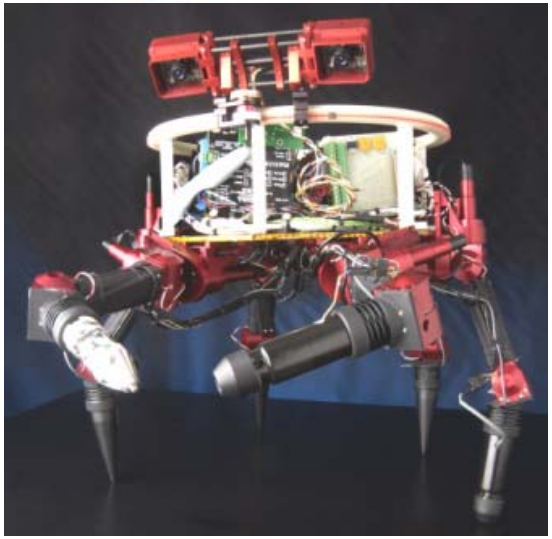


Applications of biomimetic robots

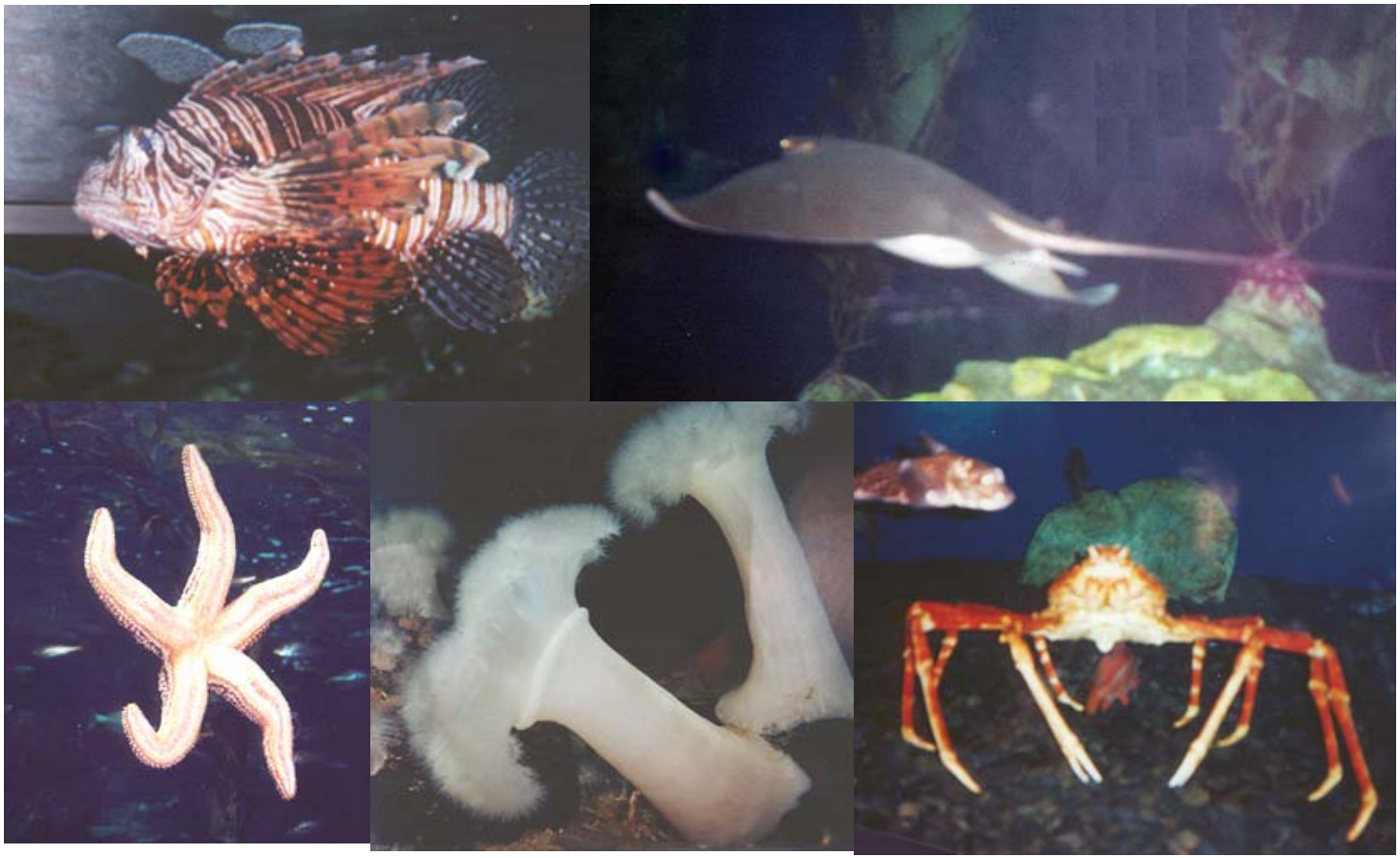
Walking forest machine for complex harvesting tasks (Plustech Oy, Finland). [http://www.plustech.fi/Walking1.html]

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

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



A challenge to EAP
Emulating sea creatures

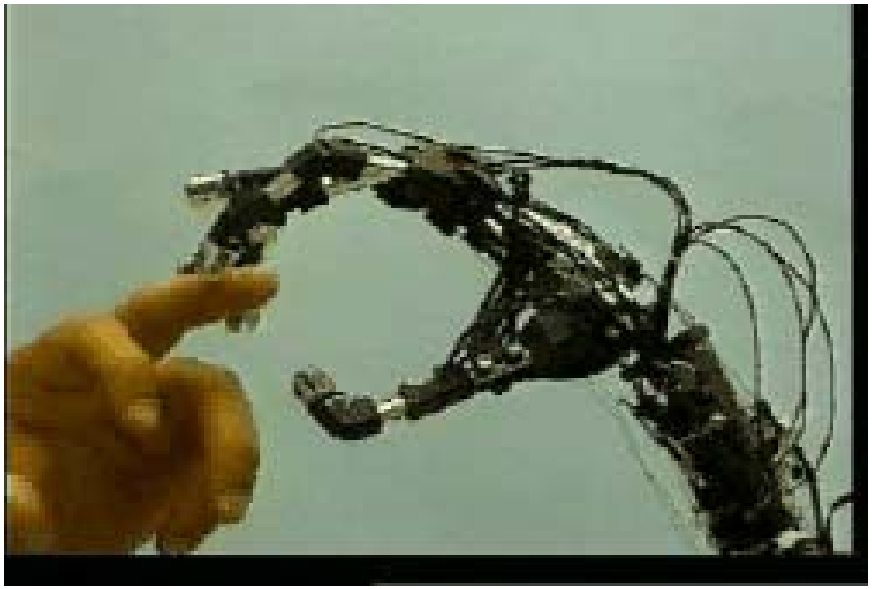


Rapid biomimetic prototyping reality

Platforms for EAP Implementation

Android making facial expressions

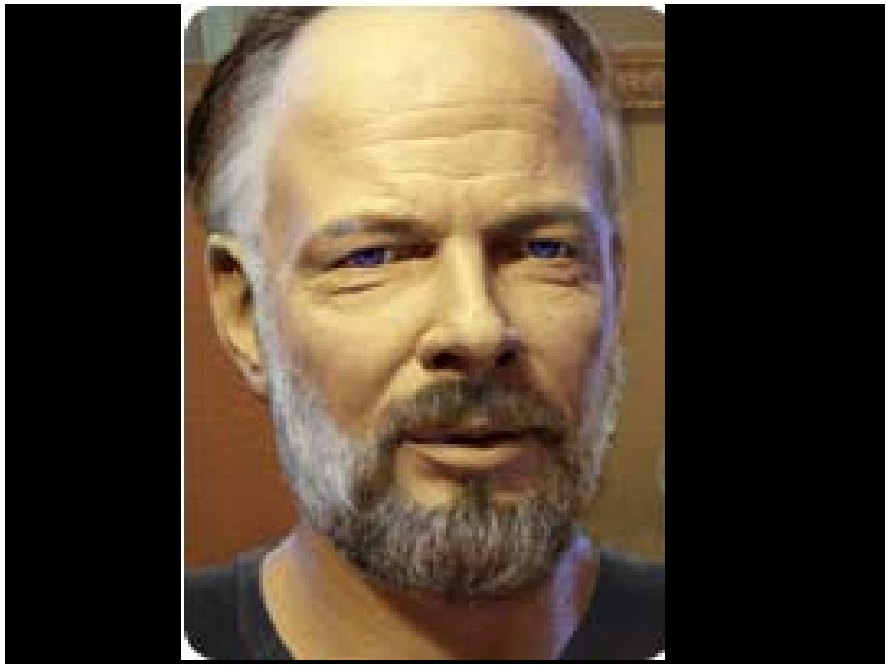
[Made by D. Hanson, U. of Texas, Dallas]



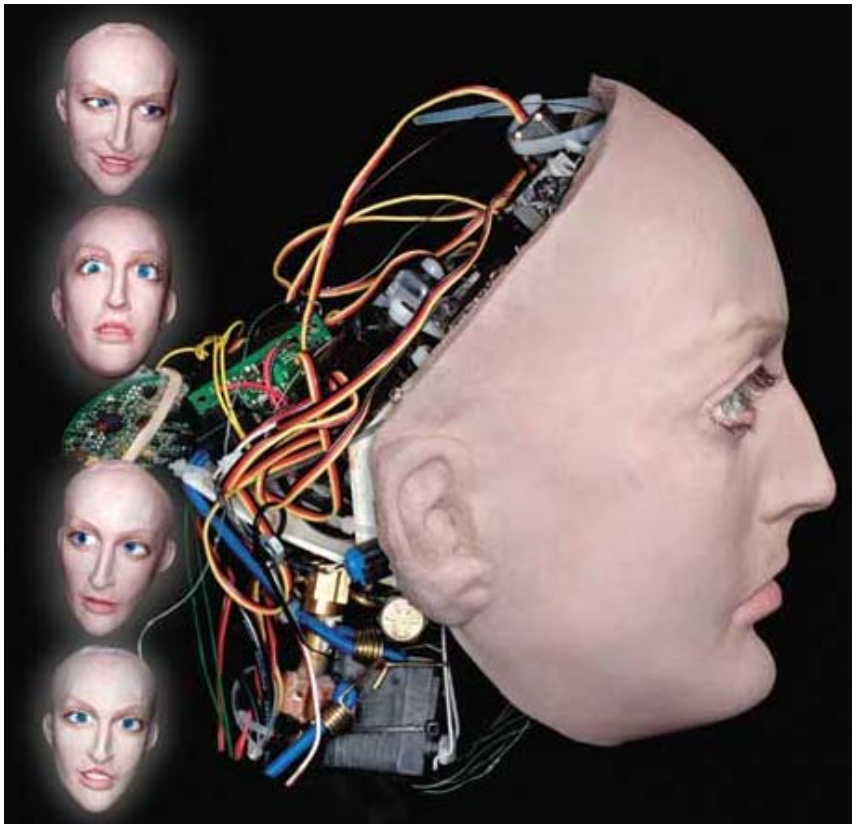
Robotic hand platform for EAP

[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

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

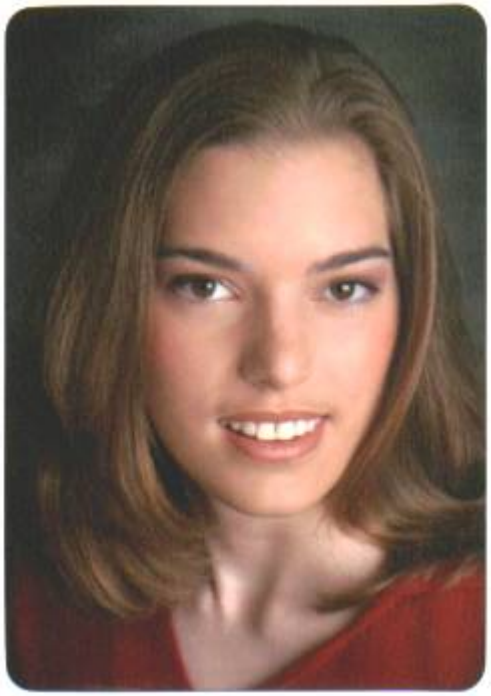
Current status

- 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 Competition 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 (currently a Student at Caltech). She is a hardworking student who mixes both education priorities and extracurricular activity ranging from recreation sports to robotics.
- Panna has taken 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 lives in Encinitas, California, which is located north of San Diego, where she enjoys shooting hoops at the YMCA and occasional walks to the beach from her home. What was once training ground during her eight-year competitive swimming regimen, the beach is now a place where she goes only for recreation to ride her boogie board and to build extreme sand castles—when she allows 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 is serving as the only student member of the San Diego Science Alliance Robotics Steering Committee, the group that first introduced her to robotics. She is also organizer of her school's participation in Science Olympiad, and on weekends, she works 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 rules of the competition

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 First Armwrestling Contest

March 7, 2005

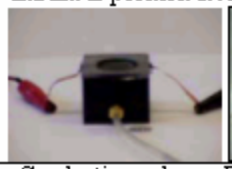
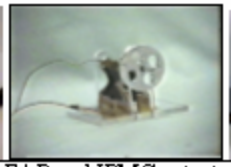
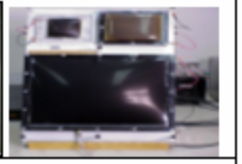
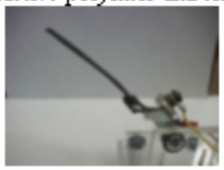
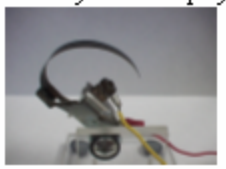
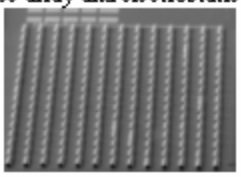
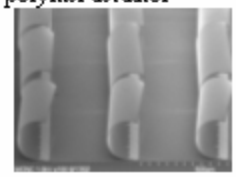
Environmental Robots Inc. (ERI), Albuquerque, NM, used dielectric elastomer and of ionic polymer metal composites (IPMC) strips – this arm lasted 26-sec.

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

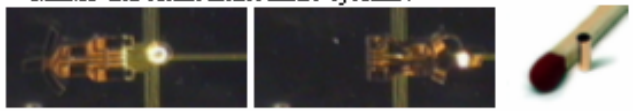
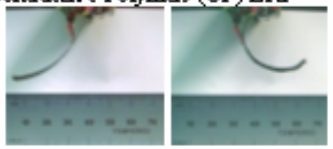
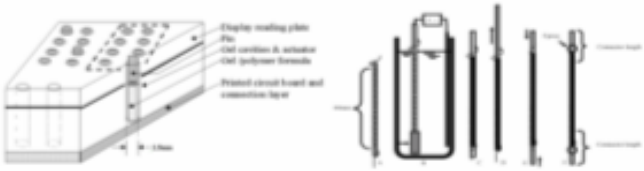
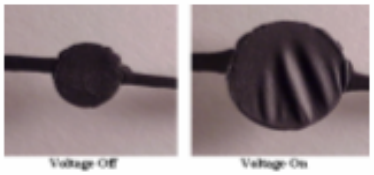
EMPA, Dubendorf, Switzerland used dielectric elastomer in 4 groups of multi-layered scrolled actuators– this arm lasted 4-sec.

Video of the three wrestling matches

EAP material and product manufacturers

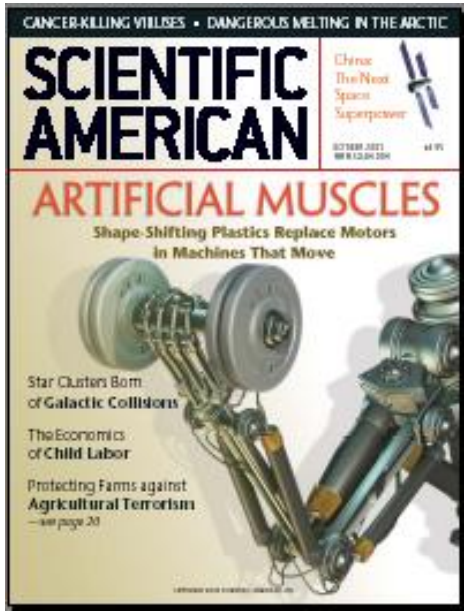
Company Name, Contact person, E-mail, Website	EAP materials/processes/products
Artificial Muscle, Inc. (AMI)* 333 Ravenswood Ave., Menlo Park, CA 94025 Alex N. Beavers, Jr., Ph.D. Chief Executive Officer; alex@artificialmuscle.com www.artificialmuscle.com *Founded by SRI International	▪ Design and manufacture 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 2003, 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

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

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.

Robotic Fish

The first commercial EAP-based product

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 evolution of the armwrestling competition will provide an exciting measure of how well the research and engineering community is dealing with the challenges to pulling the field forward.
- There is a need to document natures' inventions in an engineering form to possibly inspire new capabilities.

4. Mechanical engineering in nature and related technologies

Biomimetics

Biologically Inspired Technologies

Yoseph Bar-Cohen, JPL

Biomimetic Mechanisms

- Biological creatures can build amazing shapes and structures using materials in their surroundings or materials that they produce.
  - The produced shapes and structures within a species are very close copies.
  - They are also quite robust and support the required function over the duration that it is needed.
  - The size of a structure can be significantly larger than the species that built it, as is the case with the spider's web.
  - One creature that has a highly impressive engineering skill is the beaver, which constructs dams as its habitat on streams.
- Structures may include underground tunnels that gophers and rats build.
- Birds make their nest from twigs and other materials that are secured to various stable objects, such as trees, and their nests are durable throughout the bird's nesting season.
- Many nests are hemispherical in the area where the eggs are laid. One may wonder how birds have the capability to design and produce the correct shape and size that matches the requirements of allowing laid eggs to hatch and grow as chicks until they leave the nest.
  - The nest's size accounts for the potential number of eggs and chicks, in terms of required space.
- Plants also offer engineering inspiration, where mimicking the concept of seeds that adhere to an animal's fur, Velcro was invented and has led to enormous impact in many fields, including clothing and electric-wires strapping.
- Because of their intuitive characteristics, the use of biologically-based rules allows for the making of devices and instruments that are user friendly where humans can figure out how to operate them using minimal instructions.

Biologically inspired mechanisms

Pumping mechanisms

- Nature uses various pumping mechanisms that are also used in mechanical pumps
- The lungs pump air in and out (tidal pumping) via the use of the diaphragm that enables our breathing
- Peristaltic pumping is one of the most common biological mechanisms (e.g., digestion system), where liquids are squeezed in the required direction
- Pumping via valves and chambers that change volume is found in human and animal hearts, with expansion and contraction of chambers
- One-way valves is the key to the blood flow inside the veins (lower pressure)

Controlled adhesion

- Controlled adhesion is achieved by many organisms using a highly fibrillated microstructure.
  - The Hemisphaerota cyanea (beetle) uses wet adhesion based on capillary interaction
  - The Gecko exhibits remarkable dry adhesion using van der Waals forces. Using these adhesion mechanism, the Gecko can race up a polished glass at a speed of a ~1 m/sec and support its body weight from a wall with a single toe.

Biological clock

- Body processes are controlled by our biological clock at amazing precision
- This clock is critical to the timely execution of the genetic code to form the same characteristics for the given creatures at the same sequence (e.g., the cicada matures for 17 years and lives one week).

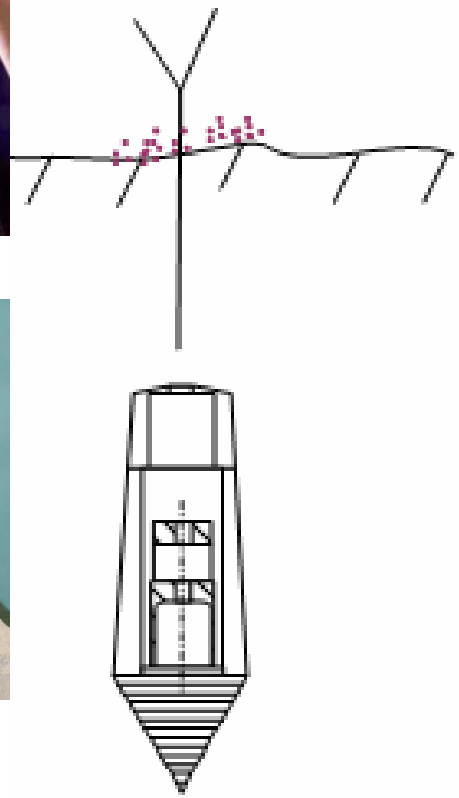
Functional surfaces in biology - mechanisms and applications (Chapter 15)

Stanislav N. Gorb, Max-Planck Institute for Metals Research, Germany

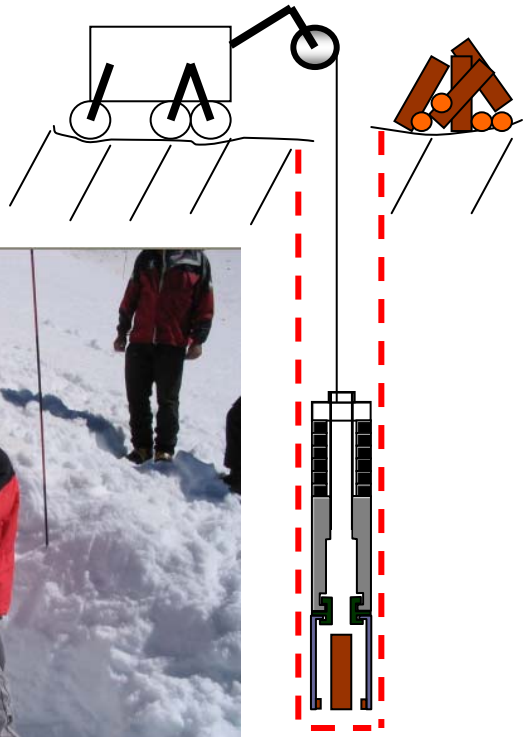
- Throughout evolution, nature has constantly been called upon to act as an engineer in solving surface-related technical problems. Organisms have evolved in immense variety of shapes and structures. Although often intricate and fragile, they can nonetheless deal with extreme mechanical loads.
- This chapter has demonstrated that many functions are based on a variety of ingenious surface-related solutions.
  - The success of biologically-inspired technological surfaces is an indication that knowledge from biology is also highly relevant for technical applications.
- One of the greatest challenges for today's engineering science is miniaturization. Many organisms have solved many problems correlated with extremely small size, during their evolution.
  - Zoologists and botanists have collected a huge amount of information about the structure of such living micromechanical systems. This information can be used to mimic them for further industrial developments.
- An important feature of the evolution of functional surfaces is the multiple origins of similar solutions in different lineages of living organisms, and in different functional systems. These examples should be the very first candidates for biomimetics. For example,
  - There is no doubt that attachment systems consisting of a pair of microtrichia-covered surfaces appeared independently in the head-arresting system of Odonata, coxal-locking devices of Neuroptera, and the elytralocking system of Coleoptera.
  - In the case of locomotory attachment devices, hairy pads appeared three times independently within insects and additionally at least two times within other animals.
  - Similar optical structures, made of different materials, have been described for insects, birds, and plants.
  - Such examples of convergence are the most interesting from the engineering point of view, because they indicate a kind of optimal solution for a particular problem.
- An engineering approach, applied after detailed studies on the natural system, involving modeling and then prototyping, would be most promising.
- In some cases, engineers can also, simply copy the surface shape and replicate it at a variety of scales and materials using available technologies of chemistry and processing.

Biomimetic ground penetators

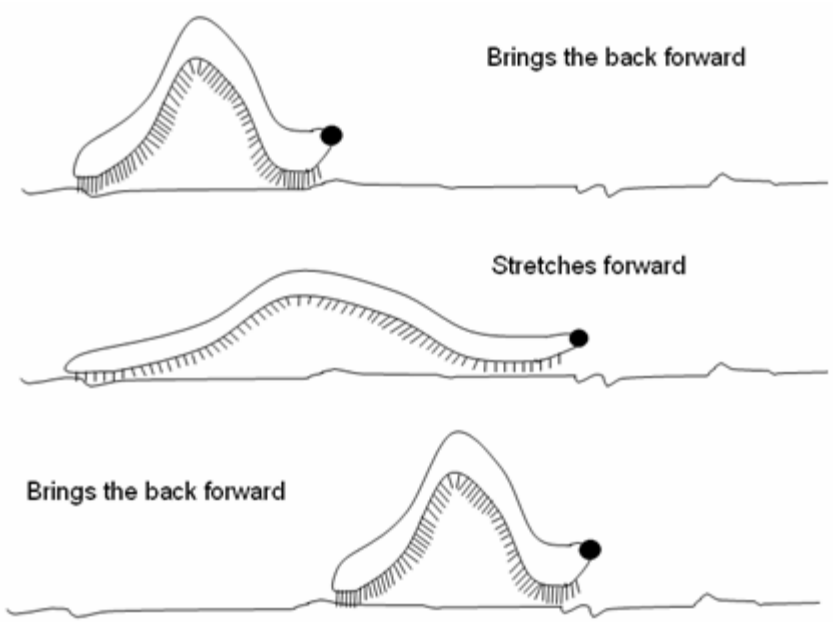
Emulator of the crab



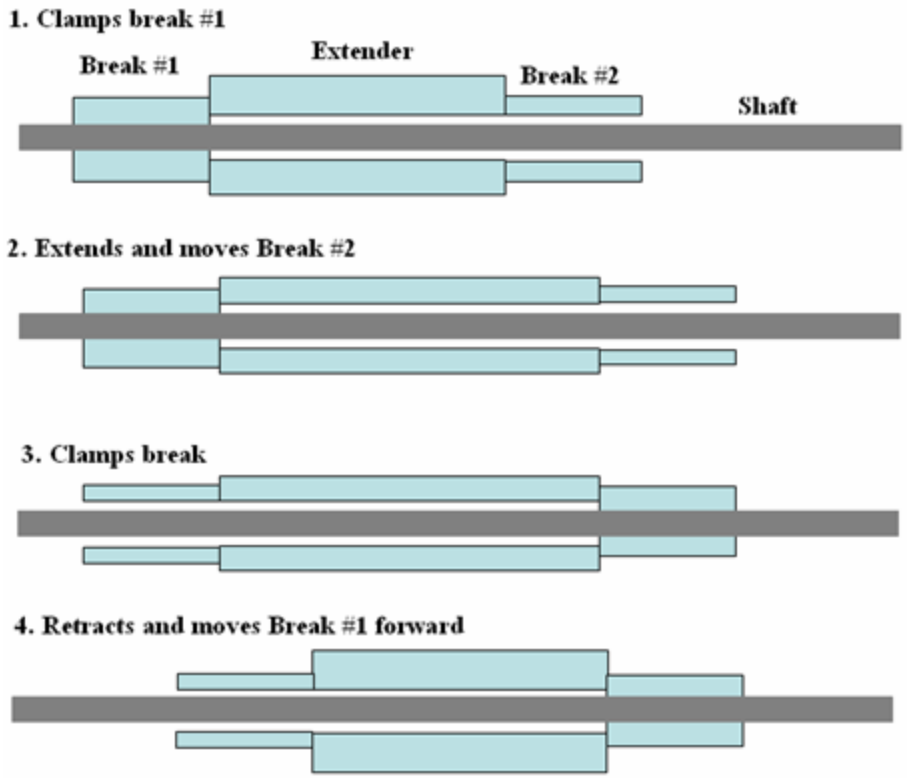
Emulator of the gopher



Inchworm motors



One of the forms of worms' mobility (the *millipede)*.



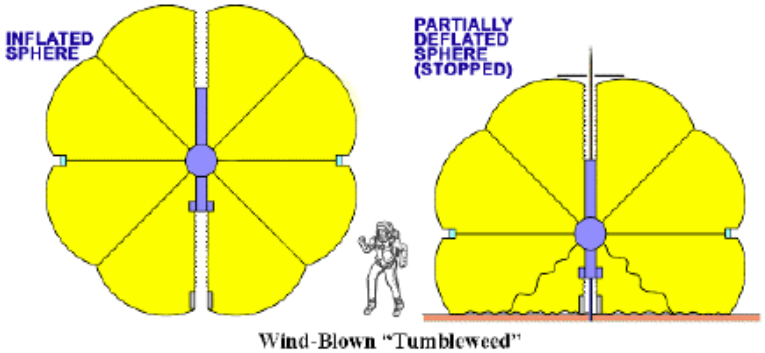
Operation sequence of a typical inchworm mechanism

Biomimetic structures and parts

Peacock tail as a hand fan

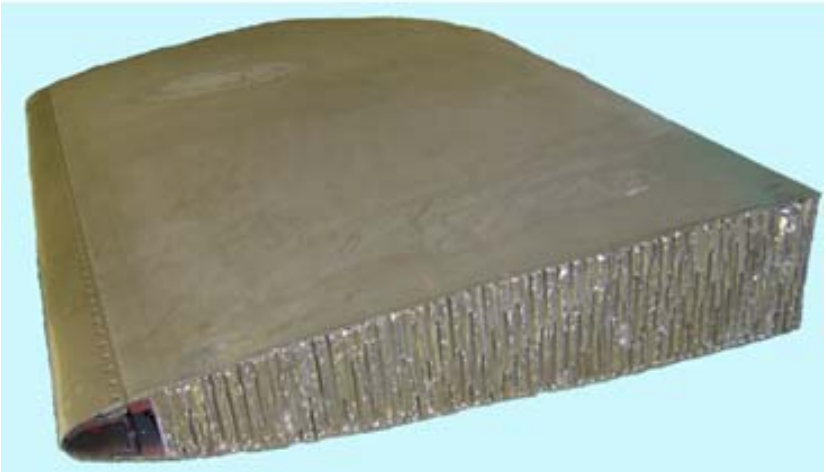
Tipuana tipu seed dispersion and helicopter blades

Tumbleweed and wind mobility



Honeycomb as a strong, lightweight structure

The honeycomb (left) and the nest of the wasp (right) is a highly effective structure in terms of low weight and high strength.



A cross section of a honeycomb structure that plays an important role in the construction of aircraft control surfaces.

Fishing nets and screens

- The fishing net is another nature invention that most likely has been imitated by humans observing the spider use of its web to catch flies.
- The concept of fiber or the string may have been inspired by the spider.
- Both the spider web and the fishing net have structural similarities and the same function of trapping passing by creatures.
- The spider uses a sticky material that helps capture the trapped insects by gluing them to the web and he knows how to avoid being glued to its own web.
- Beside the use of nets to catch fish, insects and animals, human expanded the application of the concept of the net to such tools as bags for carrying and storage of objects, protective covers against insects, and mounting stored food while allowing aeration.
- The screen, mesh and many other sieving devices that allow separation of various size objects may also be attributed to the evolution of the net.
- One may attribute the invention of the net configuration to many medical supplies including the bandage and the membranes that are used to cover burns and other wounds.

Multifunctional structures

- The micro air vehicle (MAV) has the battery integrated into the wing structure allowing greater efficiencies.
  - It used to fly for <20 min while in its new configuration this 175-gram vehicle can fly for >1-hr at ≤30 mph with two cameras onboard.
  - It is now being considered for use by three Services in both land and sea.

Ref. Steve Wax, DARPA, in DARPATech 2005

Defense and attack mechanisms in biology

- A critical aspect of the survival of various species is having effective defense and attack mechanisms to protect against predators, catch prays, secure mating, protect the young generation, procure and protect food and other essential elements to survival.

- The following are some of the biologically inspired mechanisms that were adapted by humans.
  - Camouflage
  - Body Armor
  - Hooks, pins, sting, syringe, barb and the spear
  - Decoy

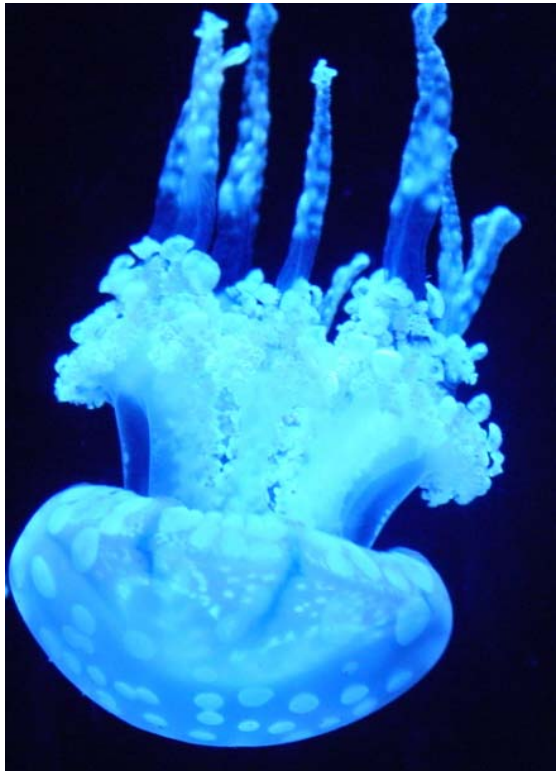
Defence and attack strategies and mechanisms in Biology (Chapter 13)

Julian FV Vincent, The University, Bath, UK

- Biology offers a great model for biomimetics in defence/attack (martial; general law enforcement) systems.
- Camouflage is area that has been examined, especially adaptive camouflage, but there is still much to be learned from nature (including ‘deception’).
- In general, camouflage and armour are inimical; the tendency is for the more primitive (= evolutionarily older) animals to be well-armoured but slow and relatively easily seen, whereas the more highly evolved ones are less well armoured, or have no armour at all, but are fast-moving and/or very well camouflaged.
  - Thus, they rely on speed and behavioural adaptiveness and subtlety for their safety.
- The inevitable conclusion is that nature often employs guerrilla techniques rather than what we think of as ‘conventional’ ones.
- This may be related to the perceived financial investment.
  - In human warfare an infantryman is seen as more expendable than the combination of a pilot and aircraft.
  - Indeed a significant reason for having a pilot is as a hostage to its expensive technology, so that the aircraft is brought back in one piece from a sortie.
- It is difficult to cover all the possibilities that exist in nature and therefore the chapter was structured in a classificatory approach, using an existing military classification as a template.
- Human has many martial devices which have their reflections in nature, but the similarities have either not been recognised or have not been developed.
- Since the outcome in nature is mostly for all parties in an intraspecific encounter to live to fight another day (or at least live), perhaps we have still much to learn.
- Generally, we have an untapped resource for biomimicry, where most of the examples quoted either have a technological counterpart or one could be realised without much difficulty.

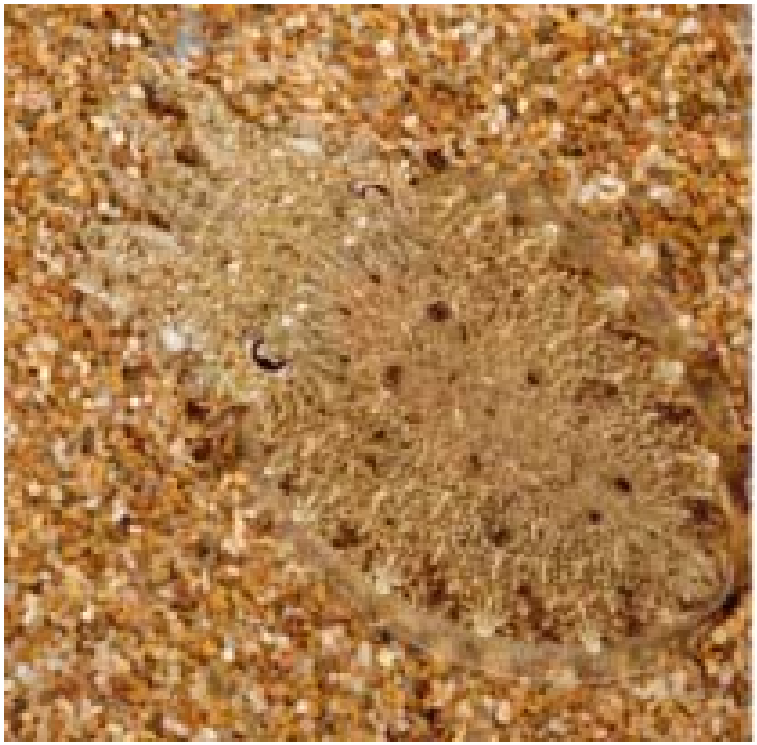
Defence and attack strategies and mechanisms in Biology (Chapter 13)

- Acoustics
  - Blast Wave Projector
  - Infrasound
  - Squawk Box
- Antilethal devices
  - Body armour
  - Passive camouflage
  - Warning colouration
  - Active Camouflage
  - 1Translucent camouflage
  - Reflecting camouflage
  - Motion camouflage
  - False target generation
- Barriers
- Slick Coating
  - Sticky Coating
  - Sticky Foam
  - Rope
  - Smoke
  - Stakes
- Biotechnicals
  - Hypodermic Syringe or Dart
  - Neuro-implant
  - Pheromones
- Elastic mechanisms
- Electrical
  - Stun Gun
- Entanglers
  - Bola
  - Cloggers
- Projectile
  - Water Stream
- Riot Control Agent
  - Chemical Mace
- Operational
  - Long Term Disablement
  - Passive Deterrents
- Physiological
  - Neurochemical
  - Diversion
- Surveillance
  - Electrosensing



Cuttlefish camouflage

- A cuttlefish can change its appearance according to the background.
- It changes its body pattern when moved from a sandy/gravel substrate to one with shells.



Courtesy of Roger T. Hanlon, Senior Scientist, Marine Biological Laboratory, Woods Hole, MA.

Camouflage and Decoy

- The chameleon and the octopus are well known for their capability to change their body color. The octopus matches the shape and texture of its surroundings as well as to release ink, which completely masks its location and activity—all the while, the octopus is a color-blind creature.
- Another aspect of the octopus' behavior is its ability to configure its body to allow traveling through narrow openings and passages.
- These include tubes, which are significantly smaller than its normal body cross-section.
- Generally, camouflage is not solely used for concealment it also allows getting close to a prey before charging ahead and capturing it by gaining the element of surprise while minimizing the response time of the prey.
  - Camouflage also provides deterrence. Some snakes, which are harmless, clone the appearance of highly poisonous snakes.
  - Some harmless flies camouflage themselves with bright colors, pretending that they are wasps.
- Minutes after birth, a baby deer is already capable of recognizing danger and taking action of passive self-defense.
  - Since often times the baby deer is left alone after birth, while the mother goes off to search for food, the baby has to rely on its ability to hide. It does this by finding shelter and taking advantage of basic camouflage rules.
  - Without training, it is able to recognize which animal poses a threat to its life. Furthermore, it is equipped with the basic skill of taking advantage of objects in its terrain (e.g., plants), to reduce its body profile by ducking low, and to use a surrounding background that match its color in order to minimize its visibility.
  - This camouflage skills, which are inherent for the baby deer, are taught in human military training as camouflage methods.
- While it is impossible to imitate the octopus' ability to squeeze its body through narrow openings (since we have bones and the octopus does not), its camouflage capabilities have been the subject of imitation by all armies.

Body armor

- The shell is means of protection that some creatures are equipped with, both on earth and underwater, and to a certain extent also in some flying insects.
- Creatures with body armor include the turtle, snail, and various shelled marine creatures (e.g. mussel, etc.). The use of shell for body protection is limited mostly to slow moving creatures.
- There are several forms of shells ranging from the shelter that is carried on the back (e.g., snails) to those with a full body cover in which case the creatures can completely close the shell.
- While the snail is able to emerge from the shell and crawl as it carries the shell on the back, the turtle lives inside its "body armor" and is able to use its legs for mobility when it is safe and hide the legs and head when it fears danger.
  - The turtle was probably a good model for human imitation in terms of self-defense.
  - The idea of body protection was adapted by humans many thousands of years ago in the form of hand-carried shields that allowed for defense against sharp objects, such as knifes and swords.
- As the capability to process metals improved, humans developed better weapons to overcome the shield and therefore forced the need for better body armor in order to provide cover for the whole body.
  - The armor that knights wore for defense during the Middle Ages provided metal shield from head to toe.
- The reliance on such armor in Japan led to a battle loss against the west in the 17th century.
- The recent evolution of the technology include the tanks providing as mobile shield and weapon.

Shelled creatures inspired human body defense armors

Decoy

- The use of decoy is as ancient as the lizards' use of its tail as a method to distract the attention of predators.
- The lizard autotomises its tail and the tail moves rapidly, diverting the attention of the suspected predator while the lizard escapes to safety.
- This method is quite critical to lizards' survival and the tail grows back again without leaving a scar.
- This capability is a great model for military strategies but also offers a model for potential healing of maimed parts of the human body.
- Success in adapting this capability could help some people with disabilities possibly allowing re-growing amputated or maimed parts of their body.

Hooks, pins, sting, syringe, barb and the spear

- Most of us have experienced at least once in our lifetime the pain of being hurt by a prick from plants - sometimes from something as popular and beautiful as the rose bush.
- Such experience can also occur when interacting with certain creatures, such as the bee. In the case of the bee, the stinger is left in the penetrated area and does not come out because of its spear shape.
- Humans adapted and evolved the concept of sharp penetrators in order to create many tools for applications in medicine, sports, and weaponry.
- These tools include the syringe, spears, fishing hooks, stings, barbs, and many others.
- Once penetrated, the hook and barb section on the head of a harpoon or an arrow makes it difficult to remove from the body of fish, animal and human body.

Mobility techniques

- Judging from the number of flying insects, birds, and marine creatures, nature has “experimented” extensively with aerodynamics and hydrodynamics.
- There are several aspects that deserve attention.
- For instance, birds can catch fish under water with their eyes closed.
- They are able to catch fish by taking into account the refraction-effect, which creates an illusion as to the location of the fish.
- Birds and various mammal predators take into account the vector trajectory of the escaping prey, as in the case of hunting a running rabbit or deer.
- These trajectories are increasingly the capability of military weapons allowing tanks to destroy a moving target while they are moving too.
- Sophisticated capabilities are used to track the moving target and either adjust the direction in flight or aim upon launch using high speed missiles or bullets.

Learning from the dragonfly

- Other aspects of flying that were inspired by biology include the ability of the dragonfly to maneuver at high speed.
- Using liquid-filled sac that surrounds its cardiac system, the dragonfly adjusts the effects of high G on its body during its flight and incredible maneuvers.
- This technique inspired a mechanism that allows pilots to fly at high mach speeds with significantly lower effects on the ability of the pilot to stay coherent.
- A liquid-filled, anti-G suit was developed by Life Support Systems, a Swiss company, and the suit is called "Libelle," which means in German "dragonfly [http://www.airpower.at/news01/0625_libelle/libelle3.htm]."
- The Libelle suit promises advantages over the pneumatic (compressed air) anti-G suits that are currently in use at various air forces including the US Air Force.
- Instead of air, the Libelle uses water to provide counter pressure proportional to the gravitation force.
- The fluid is contained in expandable, snake-like tubes that run from the neck to the ankles and over the shoulders to the wrists [http://www.txkell.ang.af.mil/news_events/suit.htm].

The inspiration of the aerodynamics of seeds

- Like biology, botany also takes aerodynamics into account. The seeds of many plants are designed with features that allow them to disperse away from their origin.
- The need to disperse can be attributed to the danger of crowding the specific type of plant in the same local area.
- The seeds use various aerodynamic techniques to be propelled by the aid of winds, and the winged seed of the Tipuana tipu (about 6.5-cm long). Such seeds have inspired designs of futuristic missions with spacecraft that would soft-land on planets with atmospheres such as Mars.
- Adapting this design may offer a better alternative for the use of a parachutes with a better capability to steer itself to land at selected sites.
- Some of the issues that are being studied include the appropriate vehicle size, acceptable descent speed in the Martian atmosphere, mass distribution and platform shape to assure stable autorotation and scalability from operation on earth to performance on Mars.

5. Mimicking biological materials and processes

Biomimetics

Biologically Inspired Technologies

Yoseph Bar-Cohen, JPL

Mimicking biological materials

- Nature materials have unique properties that are increasing being mimicked
  - Multifunctional materials and materials as integrated systems
  - Materials with effective capabilities and durability as the silks, seashells and many others
  - Just in time fabrication
- Technologies are emerging the are offering critical capabilities for the mimicking of nature including ink-printing for rapid 3D prototyping

Biological Materials in Engineering Mechanisms (Chapter 14)

Justin Carlson, Shail Ghaey, Sean Moran, Cam Tran, and David L. Kaplan, Tufts University

- The biological world utilizes an amazing range of materials that provide function and survival to organisms faced with a wide range of environmental threats.
- The biosynthesis, processing and assembly of these materials provide insight into design rules and strategies that can serve as useful templates for broader materials science and engineering needs.
- High strength fibers, toughened organic-inorganic composites, designs for efficient fluid flow, adhesion mechanisms and actuators are examples reviewed herein.
- The knowledge gained from the study of these types of complex high performance materials systems should continue to stimulate new directions in materials science, including new hybrid systems to exploit the strengths and utility of both biological and synthetic versions of future materials designs.
  - This chapter illustrates unique materials features from Nature as inspiration for new materials designs and functions: (a) silk proteins used by spiders and silkworms to construct composite encasements (cocoons) or strong and functional webs to entrap prey,
  - (b) organic-inorganic composite structures found in sea shells to form highly engineered hard tough materials,
  - (c) surfaces used to reduce hydrodynamic friction such as in shark skin, (d) modes of ‘sticking’ to surfaces used by the Gecko,
  - (e) muscles in the human body as highly engineered actuators.
- These examples provide a range of topics to consider for inspiration of the novelty in materials designs and functions optimized through evolution. The topics also provide generic insight into the underlying principles employed by biological systems to achieve remarkable plasticity in materials structure and function.
- Each of the topics listed above is reviewed with a focus on what is currently understood in terms of structure and function, a mechanistic view of the system, and the current state of the art in mimicking these systems.
- The learning curve is barely past the lag phase and it worth considering that we are inherently limited in gaining additional insight into these systems due to the complexity of the biological systems of interest, our current limited understanding of their structure and function, and our preconceived bias of how to understand these systems due to training/perspective from more traditional materials science and engineering approaches.
- The excitement with Nature as a guide to materials science and engineering is only at the beginning and there is a lot to be learned in order to elucidate the ‘rules’ that govern the processes involved.

Multifunctional Materials (CHAPTER 12)

Sia Nemat-Nasser, Syrus Nemat-Nasser, Thomas Plaisted,
Anthony Starr, and Alireza Vakil Amirkhizi, University of California, San Diego

- Multifunctional structural materials possess attributes beyond the basic strength and stiffness that typically drive the science and engineering of the materials for structural systems.
- The structural materials can be designed to have integrated electrical, magnetic, optical, locomotive, power generative, and possibly other functionalities that work in synergy to provide advantages that reach beyond that of the sum of the individual capabilities.
- Materials of this kind have tremendous potential to impact future structural performance by reducing size, weight, cost, power consumption and complexity while improving efficiency, safety, and versatility.
- Nature offers numerous examples of materials that serve multiple functions.
- Biological materials routinely contain sensing, healing, actuation, and other functions built into the primary structures of an organism.
- The human skin, for instance), consists of many layers of cells, each of which contains oil and perspiration glands, sensory receptors, hair follicles, blood vessels, and other components with functions other than providing the basic structure and protection for the internal organs.
- These structures have evolved in nature over eons to the level of seamless integration and perfection with which they serve their functions.
- Scientists now seek to mimic these material systems in designing synthetic multifunctional materials using physics, chemistry, and mathematics to their advantage in competing with the unlimited time frame of nature's evolutionary design process.
- The multifunctionality of these materials often occurs at length scales from the nano- through macro-scales and on various temporal and compositional levels.

Mimicking biological materials

- The body is a chemical laboratory that processes chemicals acquired from nature and turns them to energy, construction materials, waste and various multifunctional structures.
- Natural materials have been well recognized by humans as sources of food, clothing, comfort, and many others where, to name few, one can include fur, leather, honey, wax, milk and silk.
- Even though some of the creatures and insects that produce materials are relatively small, they can produce quantities of materials that are sufficient to meet human consumption on a scale of mass production (e.g., honey, silk and wool).
- The use of natural materials can be traced back thousands of years. Silk, which is produced to protect the cocoon of the silkmoth, has great properties that include beauty, strength and durability.
- These advantages are well recognized by humans and the need to make them in any desired quantity led to the production of artificial versions and imitations.
- Some of the fascinating capabilities of natural materials include self-healing, self replication, reconfigurability, chemical balance, and multifunctionality.
- Many man-made materials are processed by heating and pressurizing, and this is in contrast to nature which always uses ambient conditions.
- Materials, such as bone, collagen or silk are made inside the organism's body without the harsh treatment that is used to make our materials.
- The fabrication of biologically derived materials produces minimum waste and no pollution, where the result is biodegradable and is recycled by nature.
- Learning how to process such materials can make our material choices greater and improve our ability to create recyclable materials that can better protect the environment.
- There are also studies that are improving prosthetics, which include hips, teeth, structural support of bones and others.

Spider web – strong fibers

- One of biology's best "manufacturing engineers" with an incredibly effective material-fabrication capability is the spider.
- It fabricates the web to make a very strong, insoluble, continuous lightweight fiber and the produced web is resistant to rain, wind and sunlight.
- It is made of very fine fibers that are barely visible allowing it to serve its function as an insect trap.
- The web can carry significant amount of water droplets from fog, dew or rain.
- This makes the web visible where water droplets accumulated on a foggy day.
- The web structure that is shown on the left has quite an interesting geometry with spokes, with certain length and density of sticky spiral material for catching bugs.
- The segments of the shown web are normally straight but are seen curved in this Figure resulting from the weight of the accumulated droplets.
- The net is sufficiently strong to survive this increased load without collapsing.
- The spider generates its fiber while hanging on to it as it emerges cured and flawless from its body at room temperature and at atmospheric pressure.
- The spider has sufficient supply of raw materials for its silk to span great distances.
- It is common to see webs tied in various shapes (including flat) between distant trees and the web is amazingly larger compared to the size of the spider.
- Another interesting aspect of the spider web is the fact that it is a sticky material that is intended to catch prays but the spider is able to move on it freely without concern of being self-trapped.

Honeybee as a multiple materials producer

- Another "material manufacturing engineer" found in nature is the honeybee.
- This insect can make materials in volume that far exceed the individual bee's size.
- The bee is well-known for making honey from nectar that it collects from flowers.
- The bee also produces honeycomb from wax.
- Historically, candles were made using this beeswax, but with the advent of the petroleum industry, candles are now mostly made from paraffin wax.
- Another aspect of the bee is that its body produces a poison that causes great pain, which is injected through its stinger into the body of any intruder who is perceived to endanger the bees' colony.

Swallow as a clay and composite materials producer

- The swallow produces its nest from mud and its spit, forming a composite structure that is strong.
- The nest is shaped to fit the area onto which it is built.
- The swallow builds its nest under roofs and other shelters that provide both protection and concealment. It is interesting to note that the swallows attach themselves to the wall, carrying their body weight on their claws, which secured them comfortably to stucco paint on walls.

Fluorescence materials in fireflies and road signs

- Fluorescence materials can be found in quite a few living species and these visible light-emitting materials can be divided into two types:
- Bioluminescence – a voluntary or involuntary light emission, which results from a chemical reaction.
- Fluorescence - emission of light under ultraviolet illumination.
- Bioluminescence can be found in various beetles (e.g., firefly), marine creatures (e.g., *Pyrocystis lunula*, *Gonyaulax polyedra*, and squids) as well as certain bacteria, and mushrooms.
- These materials are used to attract females as in the case of the American firefly, which uses bioluminescence to deceive hetero-specific males and eat them.
- For instance, the *Photuris* females attract male fireflies by "mimicking" females of other species.
- The male firefly flashes its light in order to "declare" its presence and identity and to attract the females of its own species.
- The *Photuris* females mimic the flashing rate in its deception method. Another example of fluorescent materials is found in the glow-worm, a type of beetle (*Noctiluca*), whose wingless female glows in the dark.

Impact sensitive paint mimicking bruised skin

- Our skin is sensitive to impact leading to a purple color in an area of the skin that was hit.
- This bruising mark indicates the fact that the specific area has suffered an impact. This idea inspired researchers at the South West Research Institute in the mid 1980s to develop a surface coating as a nondestructive indicator of impact damage in composite materials.
- The need for such an indicator rose as the use of composite material increased to a level where structure that are critical to the safety of aircraft started to be introduced into military and commercial aircraft.
- US Air Force studies showed that these materials are sensitive to impact at the level that a loss of about 80% in the compression static strength was measured when an impact causes an easy to see damage to the surface, whereas a loss of 65% when the damage is barely visible.
- In order to develop an impact damage indicator, paint was mixed with an encapsulated dye and developer and was applied to the surface of composite panels.
- The micro-capsules that were used had a diameter of 1 – 10 μm and in this size they were easy to apply with conventional methods of spraying to increase the practicality of this paint.
- Tests have shown feasibility of the concept and the paint was effective in indicating the location and intensity of the impact, where the larger the impacted area the larger the indication that was formed.

Mimicking sea creatures with controlled stiffness capability

- Certain sea creatures, such as the sea cucumbers, are capable of controlling the tensile properties of their connective tissues by regulating the stress transfer between collagen fibrils *.
- Trotter et al [2000] sought to design a synthetic analogue with similarly reversible properties and have been able to demonstrate a pair of synthetic molecules that selectively and reversibly associate with one another under controlled physiological conditions.

*http://www.biochemsoctrans.org/bst/028/0357/0280357.pdf

Biology as a source for unique properties and intelligent characteristics

- Materials that are made by animals offer capabilities and properties that are often far superior to any human-made imitations.
- These material properties include hardness, fracture resistance, and lightweight - as can be found in pearls and shells of various marine species, including the abalone.
- There are also many body parts (e.g., teeth and eye cornea) that are made as layered assemblies, which are now emulated by methods such as self-assembly and ink-jet printing.
- Smart materials are increasingly evolving in various forms, with self-sensing and reaction capabilities that cause them to stretch and contract in response to heat, light, and chemical changes.
- Another aspect of biomaterials is self-healing, which is increasingly being adapted to polymer and composite materials.

Multifunctional materials

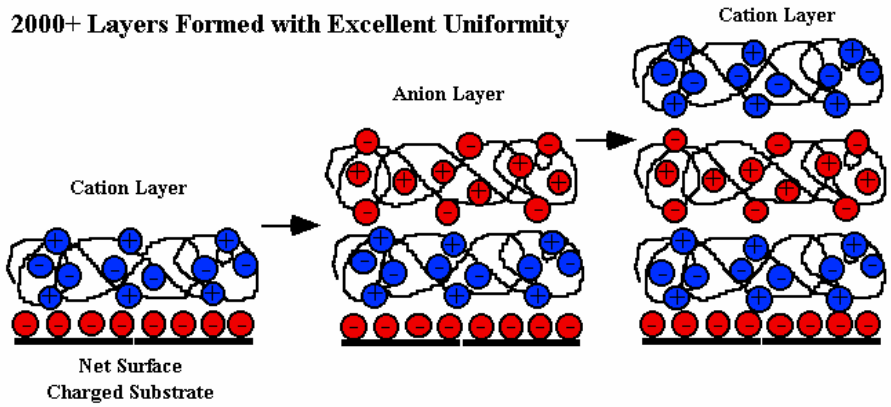
- Nature has made great efforts to use its resources effectively and besides the use of power in efficient ways including its recycling, nature also assigned multi-functions to its materials and structures.
- For example, our skin is used to encase our blood and other parts of our body, supports the regulation of the body temperature, has self-healing capability, and has many other functions.
- Also, our bones provide the required body stiffness to support it allowing us to stand, walk and conduct various critical mobility functions but it also produces our blood in the bone marrow.
- The use of materials that perform multiple tasks allowed nature to make its creatures with a lower body weight.
- The concepts of multifunctional materials and structures are being studies by many researchers and engineers and has been the subject of a DAPRA program in the early 2000s.
- Increasingly efforts are made to emulate this characteristic where multiple disciplines are used including for example applied mechanics (elasticity/plasticity, fracture mechanics, aerodynamics), materials sciences (metallurgy, composites, polymers), electronics (sensors, actuators, controls), photonics (fiber optics) and manufacturing (micro/macro structure processing).

Biomimetic processes

- There are many biomimetic processes that were learned from studying the activity of the body of living creatures.
- The imitation of biological processes ranges from operations at the level of cells to the scale of the full body.
- Imitated processes, including artificial synthesis of certain vitamins and antibiotics, have been in use for many years.
- More recently, biomimetics have been used to design navigational systems, data converters, mathematical algorithms, and diffusion processes.
- The neural network (part of the field of artificial intelligence) is a hypothetical biomimetic computer that works by making associations and guesses, and that can learn from its own mistakes.
- Examples of biomimetic processes are described throughout this book.

Electrostatic Self-Assembly of High Conductivity Thin Film Electrodes

(Fiber & Electro-Optics Research Center, Virginia Tech)



Accomplishments

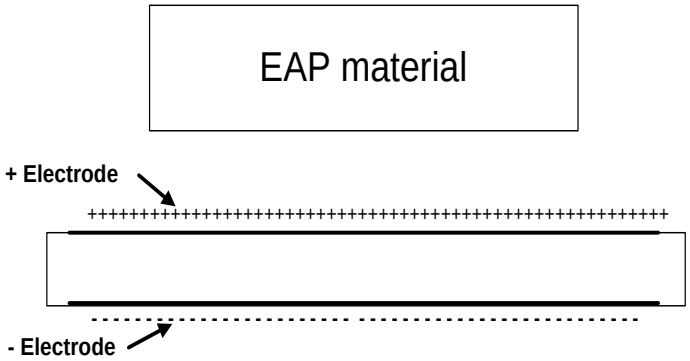
1. Designed, synthesized and measured conductivities of self-assembled metal nanoparticle-based electrodes on rigid and flexible substrates (process shown in cartoon above)
2. Initiated study of charge transfer properties of metal nanoparticle conducting thin film electrodes
3. Demonstrated conductivity on the order of $10^7\Omega$ to 1-m^{-1}, in 20 nm-thick films
4. Initiated study of barrier properties of self-assembled coating systems

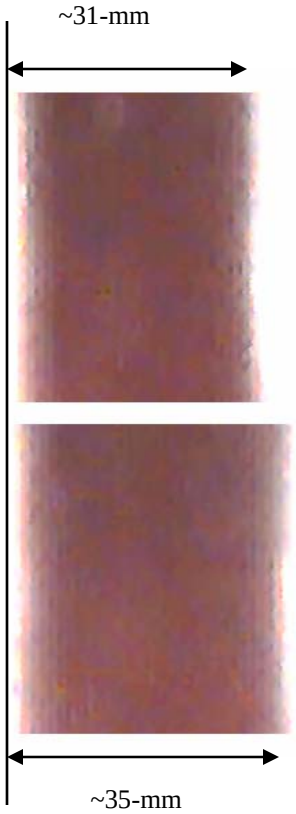
Future possibilities

1. Design, synthesize and test conductive films using different metal nanoclusters
2. Study charge transfer mechanisms, and changes in charge transfer that occur due to molecular aggregation and intermediate layer chemistry
3. Study mechanical effects on self-assembled conductive electrode thin films
4. Fabricate and deliver conductive electrode material
5. Fabricate and test barrier encapsulant and UV absorbing thin films made by ESA processing on electrode surfaces

Longitudinal EAP actuator

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

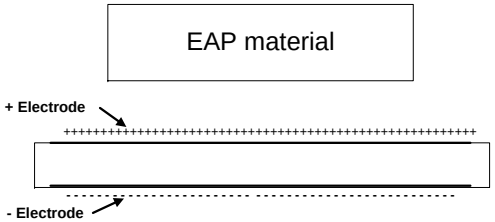




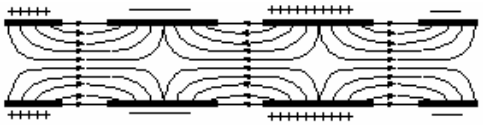
EAP film subjected to 25 V/µm induced over12% extension

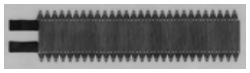
ESSP emulation of muscle

Current method of activation leads to film extension

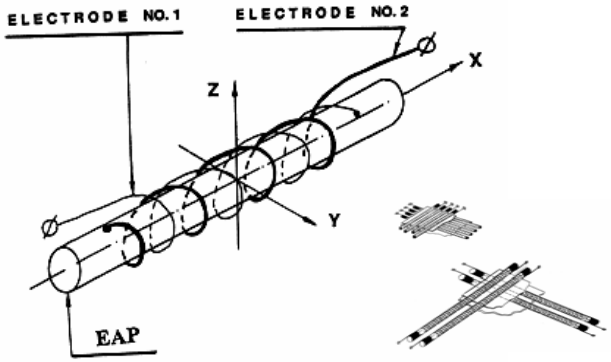


Use of interdigital electroding of films will enable shape control as well as contraction.



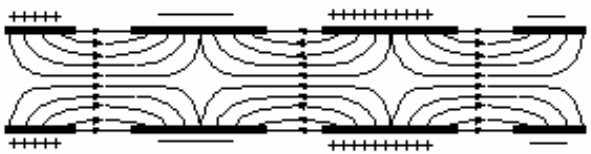


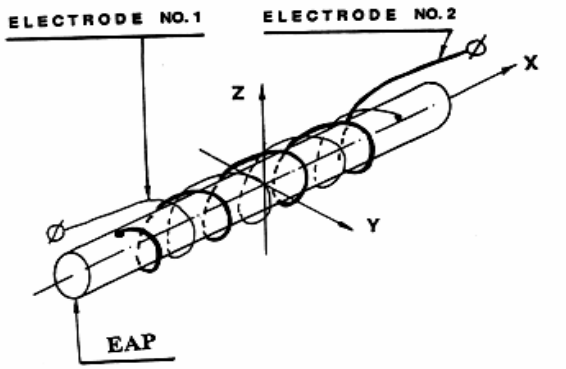
Helical electroding of fibers offer the closest resemblance of muscles where fibers can be bundled offering enhanced actuation and redundancy

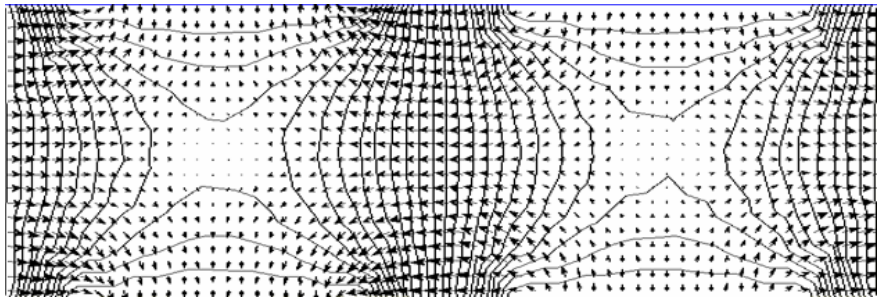


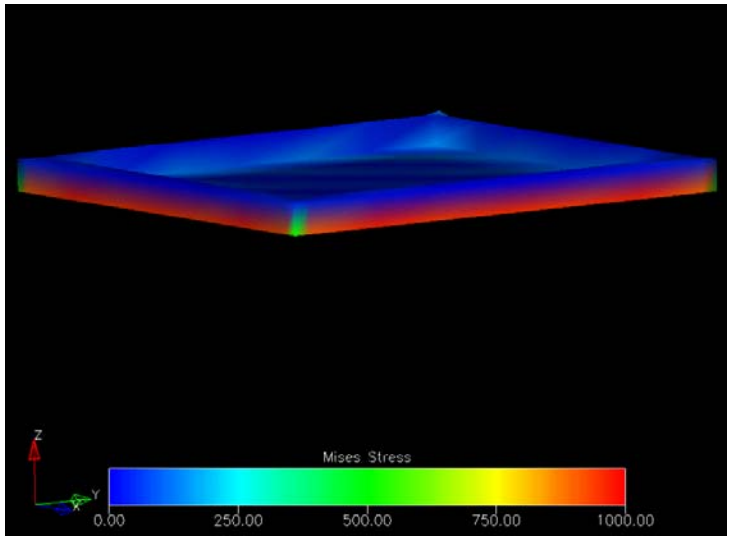
Finite element modeling of electro-statically stricted polymers (ESSP) with controlled electroding

Use of interdigital electroded films or fibers will enable shape control as well as contractile actuation.





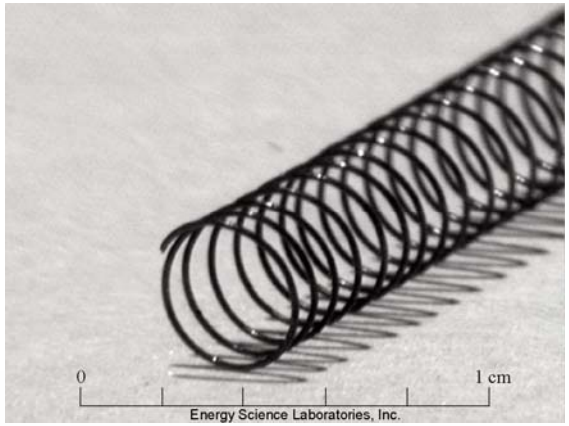


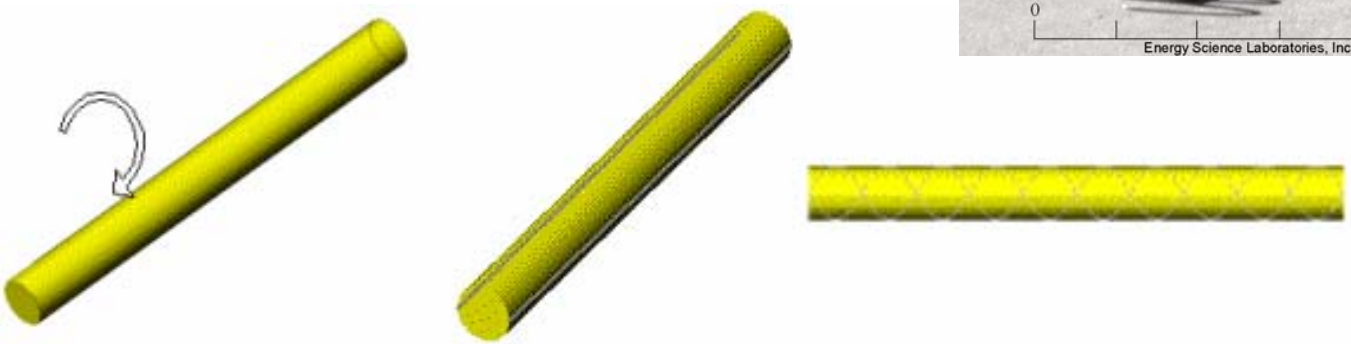


Calculated by Dr. Chang Liu, UIUC

Helically electroded fiber

Helical carbon wire made by ESLI (100-mμ carbon wire, 2.7-mm diameter helix, and 30-mm long)

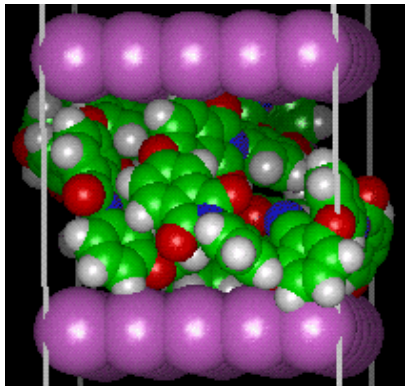




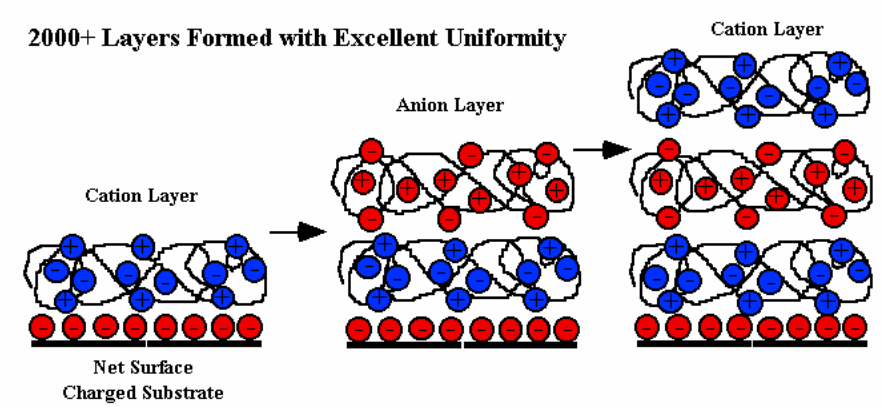
Potential fabrication process:

- Left: An elastomer fiber is twisted
- Middle: The twisted elastomer is electroded with two strips
- Right: The tension is released to form the HECEF actuator

EAP processing



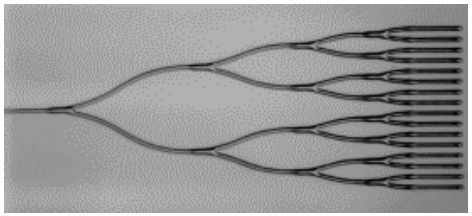
New material design tools:
Computational chemistry



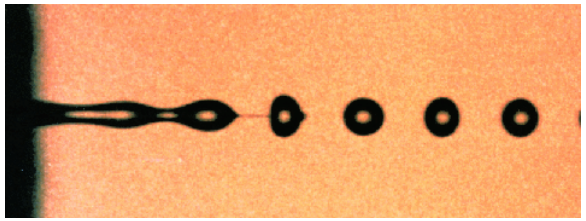
Ionic Self-Assembled
mono-layering

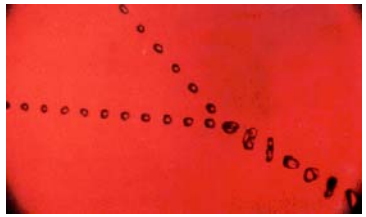
Micro-fabrication techniques:

Ink-printing



100-µm Waveguide

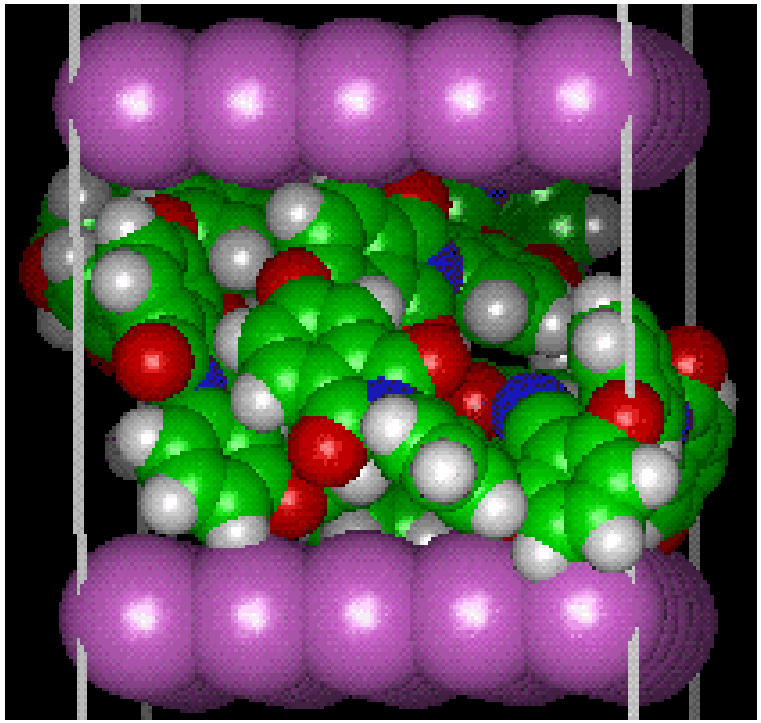




50-µm drops jet

Computational chemistry

Computational chemistry may lead to material design tools using comprehensive modeling to methodically synthesize effective new EAPs



(NASA-LaRC)

6. Current and potential applications

Biomimetics

Biologically Inspired Technologies

Yoseph Bar-Cohen, JPL

User friendly instructions

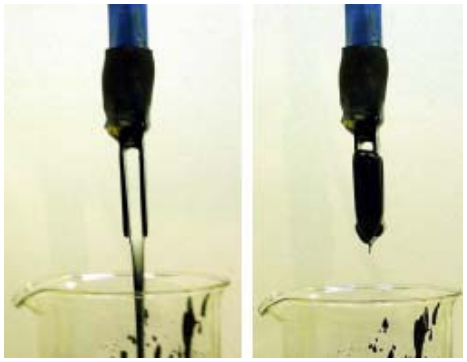
- The use of biologically inspired terms in engineering requires minimal explanation or definition:
  - Male and female connectors
  - Teeth in a saw
  - Heart to suggest the center, the head as the beginning, the foot and tail as an end,
  - Hair line, fat, eye of the …., body, digest and feed
  - Shapes are also used as recognizable terms where the *dog-bone* provides a clear description of the shape of test coupons that are used to measure the tensile module and strength of materials.
  - Structures are also widely copied; for example the honeycomb.
  - The brain to describe a smart system control - the terms intelligent or smart suggest the emulation of biological capabilities with a certain degree of feedback and decision making.
  - Performance and behavior terms include aging, fatigue, death, digestion, life cycle
- Organizational ranking
  - "High on the food chain" obviously refers to a high management level
  - Tree structure including Head, branches, right hand, watchful eye,
- Communication words that don't need any interpretation: Honey, sweet, sour, stinks, scary, rotten, facing, guts and gutsy, have roots, roots of a probe and finding own roots
- In the world of computers and software many biological terms are now part of the language
  - *Virus*, *worm*, *infection*, *quarantine*, *replicate*, and *hibernate*.
  - virtual reality as imitation of nature for simulation are the performance of materials, structures and systems.

Haptic interfaces

- Supplementing virtual-reality with the ability to “feel” remote or virtual environments is essential to making simulators and remote operators effective tools
  - Thus, an expert can perform various procedures from the convenience of the office without having to be present at the operation site.
- Remote/virtual presence requires the capability to intuitively project to the user as much sensation of the conditions at the remote/virtual site as possible.
  - The required sensation include distribution of reaction forces, temperatures, textures and other characteristics that we associate with our feeling of touching objects.
  - Using haptic (tactile and force) feedback systems allow remote/virtual feeling of mechanical forces
  - Users of such simulators may immerse themselves in the display medium while being connected thru haptic and tactile interfaces to allow them to "feel the action" at the level of their fingers and toes.
- The potential of making such a capability was enabled with a high resolution and large workspace using the novel MEMICA system (remote MEchanical MIrroring using Controlled stiffness and Actuators).
  - Electro-Rheological Fluid (ERF), which becomes viscous under electro-activation, was used.
  - Miniature Electrically Controlled Stiffness (ECS) elements and Electrically Controlled Force and Stiffness (ECFS) actuators were designed.
  - The ECS and ECFS provide users the feeling of the stiffness and forces applied at remote/virtual environments reflected via proportional changes in ERF viscosity.
  - Using such a system, surgeons may be able to conduct a virtual or remote surgery via a virtual reality display while “feeling” the stiffness and forces that are involved with the procedure.

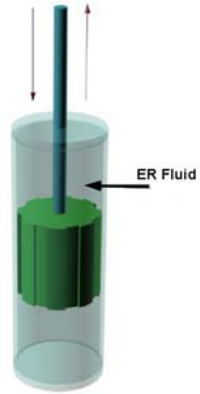
Haptic Interfacing – MEMICA System

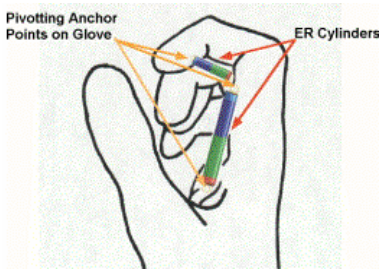
(MEchanical MIrroring using Controlled stiffness and Actuators)

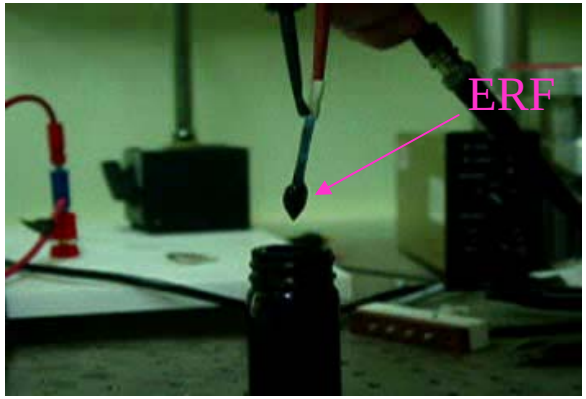


Electro-Rheological Fluid at reference (left) and activated states (right). [Smart Technology Group, UK]

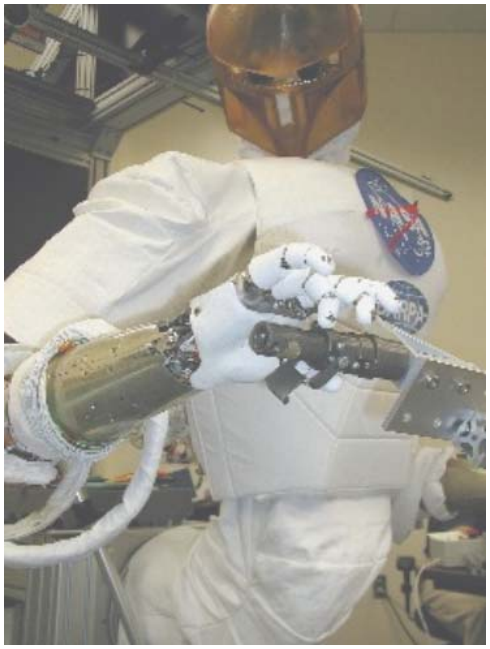
MEMICA





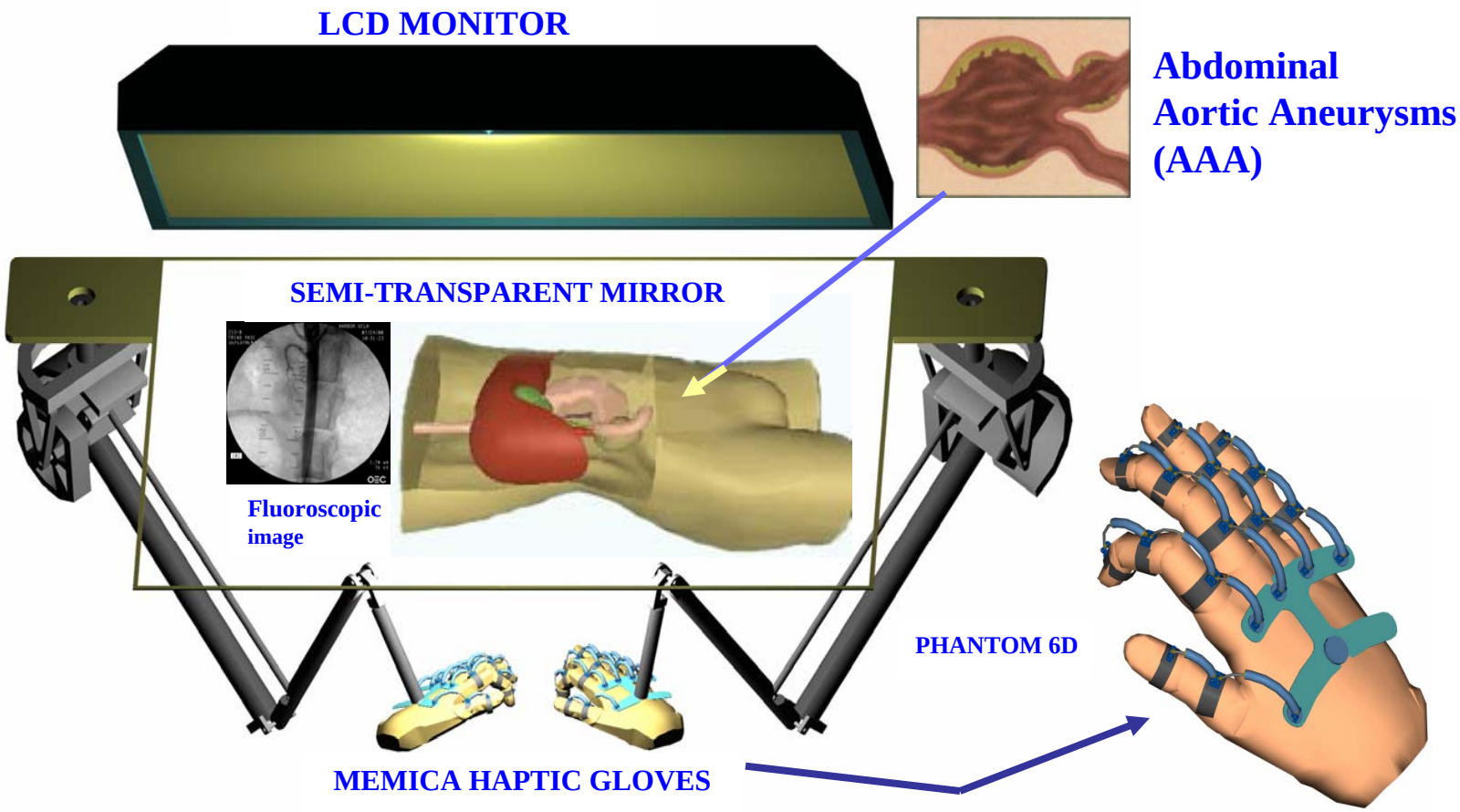


Click to see a video of ERF

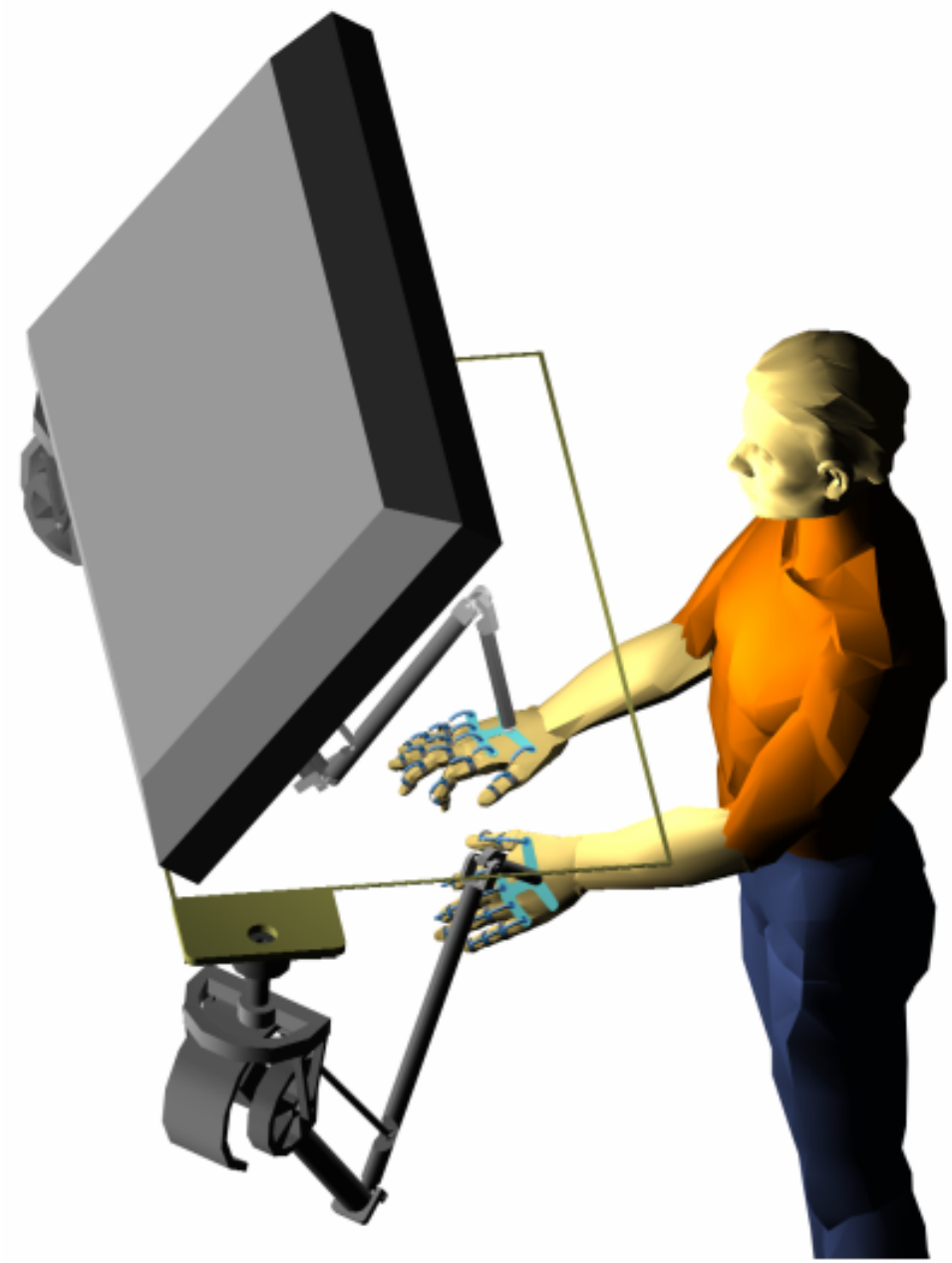


NASA JSC's Robonaut

Virtual Endovascular Telesurgery using MEMICA



Haptic system and virtual reality



Interfacing biology and machines - Applications

- The feedback can be provided with the aid of tactile sensors, haptic devices, and other interfaces. Besides feedback, sensors will be needed to allow users to protect the prosthetics from potential damage (heat, pressure, impact, etc.), just as the capability of our biological limbs.
- It is hoped to provide disabled people the ability to communicate through speech or sign to control their artificial organs.
- Interfacing of visualization and hearing devices and the human brain have already emerged where hearing devices are increasingly implanted and imaging devices are currently at advanced research stages.
- Emulating the eye focusing mechanism as well as the iris and the eyelid are found in today's cameras.
- While significant advances were already made, the human eyes combined with the brain have far superior capabilities including image interpretation and recognition, ability to rapidly focus without moving the lens location in the eye, 3-D capability, high sensitivity, and operability in a wide range of light intensities from very dark to quite bright light.

Interfacing biology and machines - Applications

- The need for such a capability has grown significantly with the emergence of small digital cameras that are now part of many cellular phones and webcams for telecommunication via computers.
- It is highly desirable to see via such cameras real-time images with the performance that approaches the human eye. Also, researchers are working to create implants that can help the vision-impaired regain the ability to see
- Increasingly, sophisticated visualization and image recognition are emerging in security systems.
- However, while lab demonstrations have been very successful, these systems still have recognition errors at unacceptable level.
- One of the benefits of this capability, once the reliability issues are overcome, would be a standard operation as part of homeland security in airports, public areas or even in our homes.

Interfacing Microelectronics and the Human Visual System (Chapter 17)

Rajat N Agrawal, Mark Humayun, James Weiland, Doheny Eye Institute, USC, Los Angeles, CA, Gianluca Lazzi, and Keyoor Gosalia, North Carolina State University

- The work in visual prostheses has come a long way from the days of laboratory research and the initial volunteer experiments.
- Today, few patients were implanted with the actual device; these devices have shown no major side-effect or complication related to surgery.
  - Some of these patients have shown encouraging responses. Artificial visual stimulus is being tried at various levels, from the retina all the way to the cortex.
  - Each type of implant has its own advantages and problems. The implant has to be not only bio-compatible, but also be able to avoid damage from corrosion in the biological spaces the device will be implanted in. Long term damage from electrical current is an issue, as is the issue with the type of vision generated by the blind patients through these implants.
- There are several challenges involved and issues to be considered during the design and development of a retinal prosthetic system, which can restore a limited form of vision.
- The electrical considerations of the prosthetic system (size and shape of electrodes, magnitude of current injection, size and shape of the implanted unit and its power dissipation, frequency, and strength of the wireless telemetry link) are closely coupled with safety considerations of the entire system (maximum allowable current densities and thermal elevation).

Interfacing Microelectronics and the Human Visual System (Chapter 17)

Rajat N Agrawal, Mark Humayun, James Weiland, Doheny Eye Institute, USC, Los Angeles, CA, Gianluca Lazzi, and Keyoor Gosalia, North Carolina State University

- The electrical issues have to be resolved to realize a safe and effective retinal prosthesis system or any other implantable neurostimulator with a large number of channels.
  - Several electromagnetic methods and computational techniques are being utilized to investigate the electrical performance characteristics of a prosthetic implant.
  - The impedance (or admittance) method coupled with the multiresolution meshing scheme (to represent the intricate details of the retinal tissues -with a 5 m resolution) appears very promising for characterizing the current spread in the retinal layers for given current stimulation and electrode array parameters.
- The computational implementation of the bio-heat equation through the FDTD method has been utilized to characterize the thermal elevation in the eye and head tissues due to the operation of the wireless telemetry link and power dissipation of the implant.
- Both these numerical techniques employ a very high spatial resolution and anatomically accurate model of the human head and eye.
- Tissues are represented by their dielectric and thermal properties as required for the specific computational investigation.
- Using these methods, it is possible to optimize the performance of an implantable neurostimulator such as the epiretinal prosthesis system with respect to effectiveness of stimulation and power dissipation.

MEMICA-based exoskeleton for countermeasures

Telepresence and Teleoperation

- Potential beneficiary of the simulation of medical therapy includes astronauts who operate at a great distance from earth.
  - The probability that an urgent medical procedure will need to be performed in space is expected to increase with the growth in duration and distance of manned missions.
  - A major obstacle may arise as a result of the unavailability of on-board medical staff capable of handling every possible medical emergency.
  - To conduct emergency treatments and deal with unpredictable health problems, the medical crews will need adequate tools and the capabilities to practice the necessary procedure in order to minimize risk to the astronauts.
  - With the aid of all-in-one type surgical tools and a simulator, astronaut(s) with medical background would be able to practice the needed procedures and later physically perform the specific procedures.
- Medical staff in space may be able to sharpen their professional skills by practicing new procedures. Generally, such a capability can also serve people who live in rural and other remote areas with no readily available full medical care capability.
  - As an education tool employing virtual reality, training paradigms can be changed while supporting the trend in medical schools towards replacing cadaveric specimens with computerized models of human anatomy.
  - Another potential benefit that MEMICA offers is the ability to provide intuitive control of remote robots.
  - These types of robots include the NASA Johnson Space Center robotic astronaut, which is known as Robonaut.

Interfacing biology and machines

- Interfacing between human or animals and machine to complement or substitute our biological senses can enable important means for medical applications.
- Of notable significance is the interfacing of machines and the human brain.
  - A development by scientists at Duke University enabled this possibility where electrodes were connected to the brain of a monkey and, using brain waves, the monkey operated a robotic arm, both locally and remotely via the Internet.
  - This research is also in progress at Caltech, MIT, Brown University and others research institutes.
- Progress in the past couple of years led to the development of chips that can recognize brain signals for movement and convert them into action.
  - Monkeys fitted with such chips were trained to move cursors on computer monitors, where such devices translate signals from the brain's motor cortex, the region that directs physical movement.
  - Advances in this field have reached the level that recently, the US Food and Drug Administration (FDA) approved, on a limited basis, the conduction of such experiments on humans.
  - For this purpose, Cyberkinetics, in Foxborough, Massachusetts is developing this capability using microchips that are implanted in the motor cortex region of five quadriplegic patients to allow them mouse control and computer access.
- The near term objective of this study is to develop neural-controlled prosthetics. The current chips last up to a year and efforts are made to develop a longer lasting wireless capability.
- Using such a capability to control prosthetics would require feedback in order to provide the human operator a “feel” of the environment around artificial limbs.

Bio-Sensors

- Living creatures are equipped with a sensory system, which provides input to the central nervous system about the environment around and within their body and the muscles are commanded to action after analysis of the received information.
- Biological sensory systems are extremely sensitive and limited only by quantum effects
- This sensory network is increasingly imitated, where we find our surrounding filled with sensors.
- The type of sensors that are used in our today's surroundings and our instruments include:
  - monitoring our property from intruders
  - releasing soap and water when washing our hands, also releasing hot air or paper towels to dry our hands
  - tracking our driving speed
  - observing our driving through intersections that are monitored by traffic lights
  - Our cars sense when we close the doors, whether there is sufficient air in the tires, charge in the battery and oil in the engine, and if all the key functions are operating properly
  - Sensors also control the flow of gasoline to the ignition system in our cars to optimize gas consumption.
  - Similar to the ability of our body to monitor the temperature and keep it within healthy acceptable limits, our habitats, working, and shopping areas have environment control to provide us with comfortable temperatures.
- Pressure, mechanical, temperature, optical and acoustical sensors are widely in use and efforts are continuously being made to improve their sensing capability and reduce their size and the required power while mimicking ideas from biology.
  - Such sensors include adapting principles from the eyes to camera, the whiskers of rodents as sensors for collision avoidance, and acoustic detectors that imitate the sonar in bats.

Biologically Inspired Optical Systems (Chapter 11)

Robert Szema and Luke P. Lee, UC Berkeley

- Of the five senses, the mechanism of sight is perhaps the most diverse in the animal kingdom.
  - There exist at least eight generalized types of optical systems, with numerous variations within each classification.
  - This is to be expected, as each animal eye is tailored to the specific needs of its owner.
  - From the defense-oriented pinhole clam eye to the night-adapted owl eye, nature has provided a plethora of examples to study and emulate.
- The ability to reproduce biological optical systems using manmade materials has applications in navigation systems, specialized detectors, and surveillance cameras.
- Of late, there has been particular interest within the military which has provided much of the funding towards research in this field.
- Advancements in materials science and manufacturing technologies have shown to be invaluable in the construction of biomimetic optics.
- Biomimetic optics is a relatively new and expanding field, although it can be argued that older technologies, such as photographic cameras, already mimic biology by having analogous structures (i.e. glass lens to biological lens, film to retina, etc.).
  - This chapter is devoted to those optical devices which, by their design, seek to imitate living organisms.
  - Examples are given surveying the ever-increasing attempts to reconstruct biological eyes.
  - They are roughly divided by the general classifications of the eyes they seek to replicate; that is, they are separated into biomimetic camera (single lens) eyes, compound eyes, and other approaches.

Miniature sensors in biomimetic robots

- The integration of sensors into mobile systems is critical to their operation, as it is necessary to provide closed-loop feedback to accomplish mobility tasks and other dynamic functions.
- Emulating the dimensions, density, integration and distribution of sensors in the human finger will require significant advancements in such fields as micro-electro-mechanical systems (MEMS) and nano-electro-mechanical systems (NEMS).
  - While currently the packing density of sensors per unit surface using MEMS technology is about 1-10 per mm^2 there is a long way to progress before reaching the density level of hundreds per mm^2 of the skin area of the fingertips.
- Combining the equivalence of soft skin and integrated sensors is a desired biomimetic development goal.
- An array of multiple types of sensors will need to be used to provide critical, detailed data about the environment and the performance of the various elements of mobile system.
- It is also highly desirable to see the development of miniature vision and sound receivers with real time image and voice recognition allowing rapid response to the environment in a manner akin to living creatures.
- For electroactive polymers as artificial muscles there is increasing need for soft sensors that can support the development of related devices.
  - These materials have functional similarities to biological muscles and the use of such sensors as strain gauges is not effective because of the constraining effect that results from the rigidity of the widely used gauges.

Collision avoidance using whiskers

- Whiskers provide is a very sensitive sense in various rodents
  - The whiskers of rats are extremely sensitive allowing avoidance of obstacles and finding food.
- Emulating the whiskers offers significant advantages to biologically inspired robots and such sensors have already been used in various commercially available robots, such as the BIOBbug toys.
  - The BIOBbug is an insect-like toy that operates as a swarm and it avoids collision between each other as well as other objects.

A swarm of BIObug toys marching in the desert effectively using their whiskers to avoid running into each other

Emulating bats' acoustic sensor

- The bat can move its ears in all directions, localize sound sources, and avoid obstacles, all while flying at relatively high speeds.
- The shape of the ear is different for the various bats, indicating that there is no optimal shape and that each bat species evolved its own biological solution.
- It is believed that the ear creates interference that is processed by the brain.
- The bat ear has been the subject of numerous studies including recent efforts to use it to navigate robots.
  - The directivity patterns for frequencies from 25 to 75 kHz were studied and the ears of various bats were tested by X-ray to find the internal structure and how sound interacts with the ear.
  - A rapid prototyping method was made to produce pinna-shapes, assuming that the make-up material is not a critical issue because of the large mismatch with air.
  - To convert sound to electric signals piezoelectric foils were used with an electromechanical conversion factor, d_{33}, ranging from 250-pC/N to 400 pC/N
  - To demonstrate the developed capability the emulated bat sensors were used to navigate robots.
- Current studies are focused on classifying landmarks, navigation in natural environments, make use of body movement and echo interpretation

Acoustic and elastic wave sensors

- Certain species are equipped with the ability to sense acoustic or elastic waves at great distances.
  - The elephant can rock its foot and emit vibrations that travel through the ground and are felt and recognized by other elephants at a distance of several kilometers.
  - The whale emits hyper-low frequency sound that travels over great distances in the ocean and can be detected and identified by other whales.
- The equivalent detectors that are made by humans include the accelerometers that are used to detect earthquakes and the sonar, which is used in submarines.
- The biological capability is still far superior in terms of sensitivity, spectral response and evaluation capability than any man made detection instrument.

Fire monitoring

- The jewel beetle lays its eggs in the bark of freshly burned trees using its ability to detect forest fires from a distance of about 80 km [http://www.uni-bonn.de].
  - This sensory organ, located on the underside of the beetle, consists of a pit that contains a large number of receptors that are extremely responsive to the infrared (IR) radiation created by a forest fire.
- Recently, zoologists at the University of Bonn have taken steps toward imitating this sensory capability.
  - This study led to the development of a sensor that is sensitive to infrared and automatically monitors large forest areas to trigger an early warning in the event of fire.
  - As biological imitation of the beetle's cuticulas sensory organ, a polyethylene platelet was developed, which absorbs thermal radiation with wavelength of 3μm, which is the typical radiation emitted by fierce force fire.
- The developed sensor was found to be two orders of magnitude more sensitive than commercially available IR sensors.
- This new sensor is expected to be produced at lower cost than commercial detectors and efforts to further improve its sensitivity are currently underway.

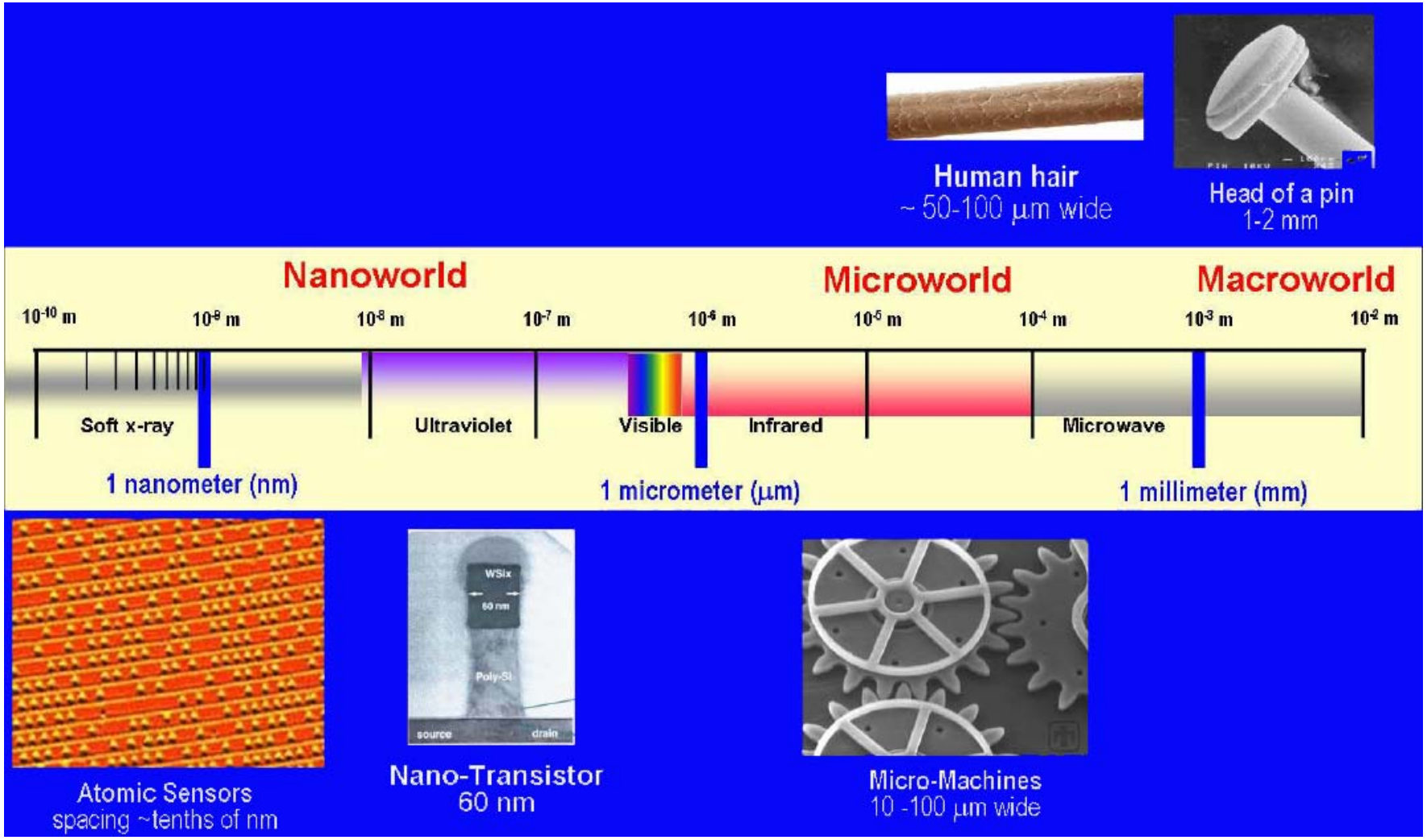
Sense of smell and artificial nose

- The topic of smell sensing has reached a level of interest and progress that led in 2004, to the Nobel Prize Award given to the researchers Richard Axel and Linda B. Buck.
- The sense of smell is our analyzer of chemicals of airborne molecules allowing us to determine presence of danger, hazardous chemicals as well as gives us the enjoyment of good food and other pleasant odors.
- Using receptors in our nose we continuously examine the content of the air we breathe where the signals are sent thru stations called glomeruli that are located in the brain's olfactory bulb.
- From there, the signal is sent to the brain where patterns of smell memories are formed and compared with previous "records."
- The sense of smell alerts us of such danger as smoke from fire, leakage of some dangerous gases and informing us of other relevant information, such as the presence of food or even perfume from other individuals.
- The detectable chemicals need to be sufficiently small to be volatile so that they can be vaporized, reach the nose and then dissolve in the mucus.
- It is estimated that our nose can distinguish between as many as 10,000 different smells.

Sense of taste and artificial tongue

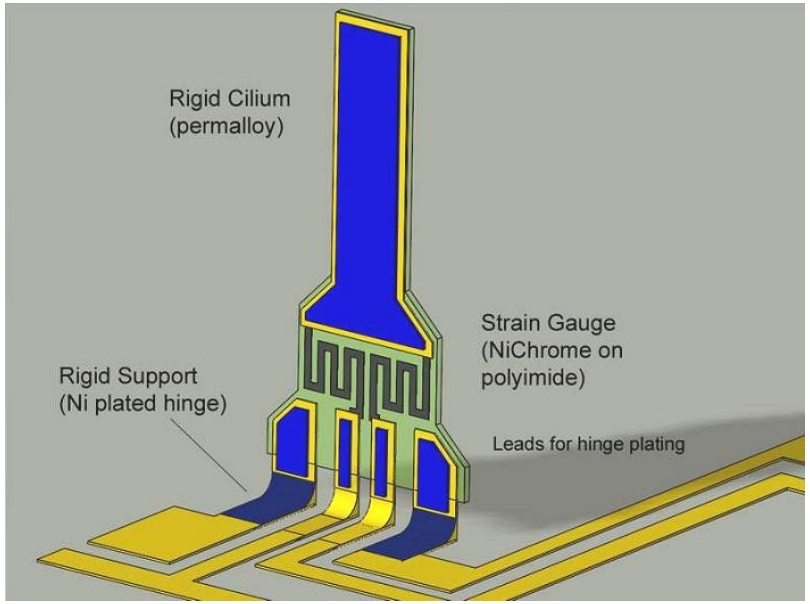
- The sense of taste is another chemical analyzer in biology and it examines dissolved molecules and ions and it uses clusters of receptor cells in the taste buds.
- Each taste bud has a pore that opens out to the surface of the tongue enabling molecules and ions taken into the mouth to reach into the receptor cells.
- Generally, there are five primary taste sensations including: salty, sour, sweet, bitter, and umami.
- A single taste bud contains 50-100 taste cells representing all 5 taste sensations.
- Each taste cell has receptors on its apical surface and these are trans-membrane proteins that bind to the molecules and ions that give rise to the 5 taste sensations.
- Several receptor cells are connected through a synapse to a sensory neuron and from there to the back of the brain, where each sensory neuron responds best to one of the 5 taste sensations [http://users.rcn.com/jkimball.ma.ultranet/BiologyPages/T/Taste.html].

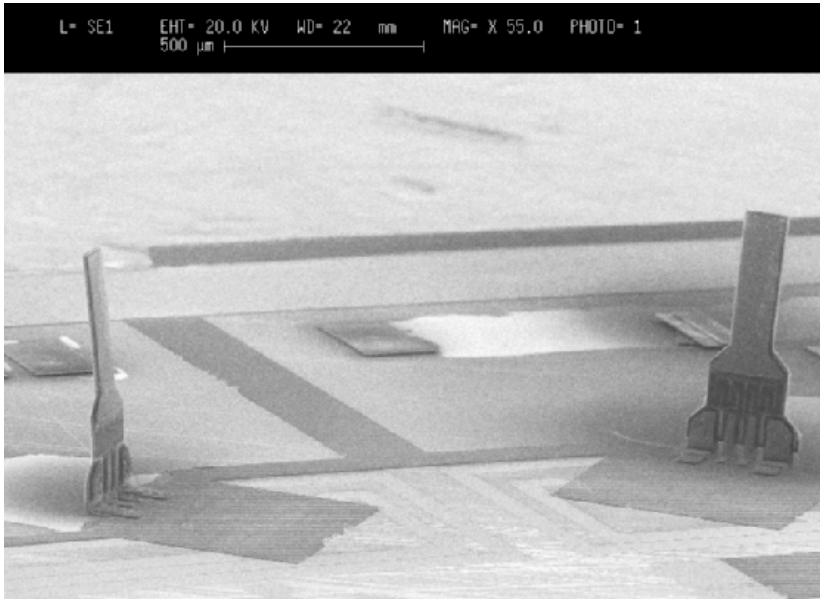
Scales in the engineering world



Cilium that bio-mimic the hair cells in fish and insects

- On the micron scale level the monitoring of air and water flow is done in insects and fish by clusters of hair cells.
- These hair cells consist of cilia that are attached to nerve cells and they sense the bending action that results from the flow.
- The displacement induces an output response from the attached nerve cell. These hair cell sensors were biomimicked to produce two types of artificial hair cell sensors. The first type has a cantilever or paddle that is parallel to the substrate, and is sensitive to flow and forces that act normal to the substrate. The second type has a cantilever that protrudes normal to substrate, where the early types were made of silicon which is brittle.





Courtesy of Jack Chen and Chang Liu, Mirco Actuators and Sensors Group, University of Illinois at Urbana-Champaign

Bionanorobotics - A Field Inspired by Nature (Chapter 7)

Ummat A., Dubey A., and Mavroidis C., *Northeastern University, Boston, MA*

- Biomimetics and its principles would greatly influence the field of nanorobotics and nanotechnology.
- The way nature is designed and the way natures solves its problems is of great interest to us because they allow us to understand basic principles that would pave to practical nanotechnology.
- The recent explosion of research in nanotechnology, combined with important discoveries in molecular biology have created a new interest in bio nanorobotic systems.
- The preliminary goal in this field is to use various biological elements - whose function at the cellular level results in a motion, force or signal - as nanorobotic components that perform the same function in response to the same stimuli - but in an artificial setting.
- This way proteins and DNA could act as motors, mechanical joints, transmission elements, or sensors.
- Assembled together, these components would form nanorobots with multiple degrees of freedom, with the ability to apply forces and manipulate objects at the nanoscale, and transfer information from the nano- to the macroscale world.
- The first research area is in determining the structure, behavior and properties of basic bio-nano components such as proteins.
- Specific problems include the precise mechanisms involved in molecular motors like ATP Synthase, and of protein folding.

Bionanorobotics - A Field Inspired by Nature (Chapter 7)

Ummat A., Dubey A., and Mavroidis C., *Northeastern University, Boston, MA*

  - The next step is combining these components into complex assemblies.
  - Next concepts in control and communication in swarms need to be worked out.
  - Nature's path is followed, mimicking the various colonies of insects and animals, and\transforming principles learned to our domain.
- Since it would require specialized colonies of nanorobots to accomplish particular tasks, the concepts of co-operative behavior and distributed intelligence need to be developed, possibly by using knew hierarchical and other techniques.
- Principles like self replication are the ones of greatest importance for the field of nano robotics.
- It is this life mimetics which will enable us to design and fabricate the future nanorobots having immense capabilities and potential.
- These would require innovative materials (intrinsic materials) and fabrication methodologies, with due regard to well-known manufacturing- and applications-related safety concerns.
- The safety issue is of paramount importance in this field for researchers and scientists.
- The proposed bionanorobots would be completely controlled molecular devices and are far from being dangerous to society.
- Though these devices would have many unique capabilities, which are not seen currently, they are harmful as projected in science fiction movies and books.
- There is an increasing need for educating the community about the exact nature of this research and its essential differences with the projections of the science fiction community.

MEMS

MEMS enables performance

- Accelerometers, inertial guidance devices, and uncooled infrared detector arrays are outstanding examples of the controlled multi-functional integration of mechanics and electronics on a single chip.
- With MEMS technology, parasitic losses can be significantly reduced by closely locating a sensor and its first-stage preamplifier on the same chip.
- Additional bonding and attachment of these chips to other electronic and photonic building blocks—known as heterogeneous integration—enables additional performance enhancement and improves packaging.

Smaller is better

- Some of the successes include miniaturized systems such as chip-scale atomic clocks.
- A Micro Gas Analyzer demonstrates what can be achieved by shrinking the various types of devices associated with common instrumentation such as chemical gas analyzers.
- Ultra-miniaturization allows extremely high surface-to-volume ratios that afford us the unprecedented ability to preconcentrate, separate, and detect the chemical constituents in an unknown gas mixture.
- Potentially hazardous substances can be separated from a background of multiple inert and benign interferrents at the level of parts per trillion with no ambiguity.

MEMS are reliable

- The physical fatigue and failure mechanisms that govern mechanical behavior in macroscale materials don’t seem to be as prominent in MEMS devices. Some of the MEMS devices have been cycled up and down 10^{16} times without failure.
- The RF switches for radar applications are based on movable electrical contacts that have demonstrated reliable switching operation over 100 billion times. This is like flipping a light switch on and off once a second for over 3,000 years.

Nano Electro Mechanical Systems (NEMS)

- NEMS may includes the integration of sensors, actuators, electronics, photonics, energy, fluidics, chemistry, and biology into a meaningful system enabled by sub-micrometer science and engineering precision.

NSTI Nanotech 2006

Boston, Massachusetts, May 7-11, 2006

2006 NSTI Nanotechnology Conference and Trade Show

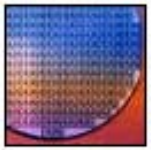
May 7-11 2006, Hynes Convention Center, Boston, Massachusetts

9th Annual - Join 300 Exhibitors & 3,000 Attendees

Announcement & First Call for Papers

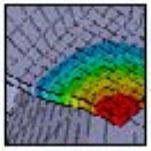
Abstracts Due: November 18th, 2005

Scheduled Industry Sessions



Electronics
- Devices, Processes
- Nano Photonics
- Spins, Quantum
- Nanowires

Computational
- Atomic Simulation
- Mesoscale Modeling
- Numerics (ICCN)
- Comp. Biology



Design & Modeling
- Microsystems
- Compact Modeling
- Computer Aided Design
- Microfluidics

Telecommunications
- MEMS, NEMS
- Nanoscale Devices
- Active Devices
- RF Devices

Displays & Optics
- Organics
- MOEMS & MEMS
- Optoelectronics
- Nano Photonics

Health Sciences
- Cancer Treatment
- Drug Delivery
- Sensors & Diagnostics
- Medical Imaging

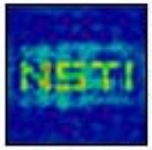
Nano Biotechnology
- Bio Molecular Analysis
- Microfluidics
- Tissues, Cell Handling
- Bio Sensors, Arrays

Personal Care
- Nanostructured Fluids
- Condensed Matter
- Colloids & Vesicles
- Soft Nanotech

Food
- Food Industry
- Colloids
- Surfaces and Flims
- Soft Nanotechnology

Polymers
- Surfaces & Interfaces
- Additives & Particulates
- Soft Materials
- Composites

Materials
- Nano Particles
- CNT Devices
- Self Assembly



Surface Science
- SPM, STM
- Functionalization
- Characterization

Coatings
- Thin Films, Electronics
- Smart Coatings
- Optical Coatings

Transportation
- Fuel Cells
- Advanced Materials
- Corporate

Environmental
- Protection
- Remediation
- Bio & Chem Sensors

Microelectronics role in biomimetics

Microelectronics is needed in many areas of biomimetics:

- Making microchips that are biologically inspired
- Use microchips to produce biomimetic mechanisms, devices, robots, etc.
- Produce devices that augment, support or replace human organs or interfacing instruments to the human body (e.g., hearing, seeing, or obtain mobility control instructions from the brain)

Molecular Design of Biological and Nano-Materials (Ch. 8)

Shuguang Zhang, Hidenori Yokoi and Xiaojun Zhao, MIT

- Many grand challenges remain in the post-genomic era. One of which is the fundamental understanding of membrane biology, namely, the study of the structure and function of membrane proteins, and specifically, the elucidation of high-resolution structures of integral membrane proteins.
- Nearly all cellular signal transduction cascades occur through membrane proteins.
- All our senses including sight, smell, hearing, taste, touch and temperature sensing, use membrane proteins for us to communicate with the external world. Many important drugs used as human therapeutics act through their interaction with membrane proteins.
- Yet, despite much effort in last few decades, little is known about the intricacies and function of many membrane proteins at present.
- Thus, meticulous and systematic determination of high-resolution membrane protein structure will not only further our understanding of proteins as a whole, but also will enhance our knowledge of signal transduction and accelerate development of ultra-sensitive sensing devices.

Molecular Design of Biological and Nano-Materials (Ch. 8)

Shuguang Zhang, Hidenori Yokoi and Xiaojun Zhao, MIT

- Although membrane proteins are composed of at approximately one-third of total cellular proteins and carry out some of the most important functions in cells, only ~100 membrane protein structures have been elucidated.
- This is in sharp contrast to ~28,000 non-membrane proteins structures that have been solved [http://www.rcsb.org/pdb/].
- The main reason for this delay is due to difficulty to purify and crystallize membrane proteins because removal of lipids from membrane proteins affects protein solubility and conformation stability.
- Despite a variety of detergents and lipids as surfactants have been used to facilitate solubilize, stabilize, purify, crystallize and manipulate the membrane proteins for over the several decades, how detergents interact with membrane protein to impact its structure and functions and how to choose good detergents for the right membrane proteins remain largely unknown.
- This is partly due to complexity of membrane protein-detergent-lipid interactions and lack of a “magic material” detergents.
- Therefore, the need to develop new material is urgent.
- Recent experiments show that these peptide detergents are excellent materials for solubilize, stabilizing and crystallizing several classes of diverse membrane proteins.

Robotics emulating biology

- These simply designed peptide detergents may now open a new avenue to overcome one of the biggest challenges in biology -- to obtain large number of high resolution structures of membrane proteins
- The introduction of the wheel has been one of the most important human inventions - allowing humans to traverse great distances and perform tasks that would have been otherwise impossible within the life time of a single human being.
- While wheel-locomotion mechanisms allow reaching great distances and speeds, wheeled vehicles are subjected to great limitations with regards to traversing complex terrain that have obstacles.
- Obviously, legged creatures can perform numerous functions that are far beyond the capability of an automobile.
- Producing legged-robots is increasingly becoming an objective for robotic developers and considerations of using such robots for space applications are currently underway.
- Operating robots as colonies or in flocks is a growing area of robotic research.
- Bio-inspired mechanisms are not only based on legs
  - Since wind is blown throughout Mars, producing a spacecraft that imitates the tumbleweed offers an attractive option.
  - The tumbleweed inspired the design of a mobility system that uses wind rather than a power-consuming mechanism.
  - The tumbleweed has inspired a futuristic lander that is currently being investigated as a potential vehicle for mobility on Mars.

Robotic biomimesis of intelligent mobility, manipulation, and expression (Ch. 6)

David Hanson, University of Texas at Dallas and Human Emulation Robotics, LLC

- Clearly the future glows for bioinspired robotics.
- Many trends are showing high degrees of functionality, and yet are increasing rapidly in function: computational hardware, materials, software, and mobility are examples.
- Yet, daunting quantities of work remain to create robots that are as capable as animals or humans.
- In fact, the increasing functionality of biomimetic robots and AI results in humbling insights regarding the complexity of the bio-sytems, which let us know how much we yet know about life.
- Future work includes the improved software integration would accelerate the functionality of social robots and the advancement of automated design and prototyping systems for robotic systems from macro scale facial expressions and locomotion systems, to microscale actuation and electronics.
- Additionally, the biosciences need to further discover what makes animals so effective, and engineers need to replicate these discoveries in technology.
- As the economy of biorobotics continues to expand, largely bolstered by the ongoing trends of increasing functionality, there should be ample resources for future research in this exciting field.

Robotic biomimesis of intelligent mobility, manipulation, and expression (Ch. 6)

David Hanson, University of Texas at Dallas and Human Emulation Robotics, LLC

- At some point if the trends continue to extremes, our biology may be difficult to distinguish from our technology, and in many ways our human identity will be challenged.
- As the technology advances, it will be worthwhile to ask questions regarding the ethical employment of the technology.
  - Will robots, like animals and humans, be afforded rights?
  - What happens if they become conscious?
  - What happens if they get smarter than us?
- Accelerating progress in robotics clearly implies that these questions are migrating out of speculative fiction and philosophy, and into reality, faster than many may think.

Biomimetic and Biologically Inspired Control (Chapter 16)

Zhiwei Luo, Shigeyuki Hosoe and Masami Ito, RIKEN BMC, Japan

- Traditional biomimetic researches mainly abstract the *specific functions* of *specific biological systems* under *specific environmental conditions*.
- As a result, many artificial systems such as airplanes, computers as well as present robots were generated.
- These efforts not only realized but also greatly improved the specific functions within artificial systems, sometimes far beyond the biological systems.
- However, as seen from the system flexibility, diversity, and the environmental adaptability, there still exists too large a gap between the biological and artificial systems.
- This gap exists not only at the material levels such as muscle and skeletal structures but also at system control level.
- In this chapter, we have introduced some of the recent researches from the point of view of biomimetic control.
- Especially we have concentrated our discussions on how to organize the system redundancy, the optimal motion formation and the environmental adaptive control.
- There are also many other issues, such as *autonomous decentralized system control* and *hybrid system control*, that didn't be mentioned here but are basically important in biomimetic control.
- An autonomous decentralized system is a system in which the functional order of the entire system is generated by cooperative interactions among its subsystems.
- Each subsystem has the autonomy to control a part of states of the system. It is well known that biological systems possess this autonomous decentralized characteristic.

Biomimetic and Biologically Inspired Control (Chapter 16)

Zhiwei Luo, Shigeyuki Hosoe and Masami Ito, RIKEN BMC, Japan

- For example, animal movements are generated by the cooperation of many motor neurons.
- These motor neurons control muscular fibers to generate different movements. Rhythmic movements, such as walking, flying and swimming, are generated by the control from the mutually coupled endogenous neural oscillators.
- The rhythmic moving patterns can be changed with respect to the environmental conditions as well as various objectives.
- The walking movement of a cat is a typical example. Here, the periodic motions of each limb cooperate with each other to generate stable gait patterns. As the cat moves faster, the gait pattern changes from “walk” to “trot”, and finally to “gallop”.
- Although the gait changes discontinuously, the speed of the body movement varies continuously. This pattern switching behavior can be formulated based on the *bifurcation theory* of nonlinear dynamic systems.
- In addition, the *graph structure* of the interaction network between all subsystems and the *time delay* of the interactions are important to determine the over system’s performance such as synchronization.
- On the other hand, if the system contains both *continuous time-driven* and *discrete event-driven* dynamics, it is called *a hybrid system*.
- Human brain has a high ability to mix discrete logical thinking with dynamic body movements control simultaneously.
- It realizes the diversity of the movements with respect to the environmental conditions as well as task requirements.

Biomimetic and Biologically Inspired Control (Chapter 16)

Zhiwei Luo, Shigeyuki Hosoe and Masami Ito, RIKEN BMC, Japan

- The biological research on *basal ganglia* suggests that such kind of a skillful optimal motion pattern scheduling function is generated through the interaction between the *basal ganglia* and the high level *motor cortex*.
- Nowadays, hybrid system arises in a large number of application areas.
- However, the problem of the hybrid system is inherently difficult because of its combinatorial nature. A straightforward application of the available frameworks faces the limitation of computational complexity and lacks the theoretical prediction of system properties.
- Hybrid systems can be formulated by many kinds of models, such as piecewise affine (PWA) system, linear complementary (LC) system and mixed logical dynamical (MLD) system, *ect*..
- The equivalence between each model formulation was studied. For the MLD system, several powerful *mixed integer quadric programming* (MIQP) algorithms have been proposed to solve the on-line optimization procedures.
- In robotic applications, recently, modeling and control of dexterous multi-fingered hand operations and multi-legged dynamic walking movements are studied from the hybrid system point of view.
- But still few theoretic results have been achieved, and there remain many challenging problems in biomimetic control research.
- It is expected that, theoretical study of hybrid system control may also lead to a better understanding of biological motor control functions at the high level of brain motor cortex and basal ganglia.

Legged robots

- In unplanned terrain walking robots have superior advantage over vehicle with wheels. However the control of the mobility mechanism is extremely complex.
- Effective algorithms have been developed that allowed making legged robots that autonomously run and walk up a steep incline.

DARPATech 2005 – Steve Wax

Robotics emulating biology (cont.)

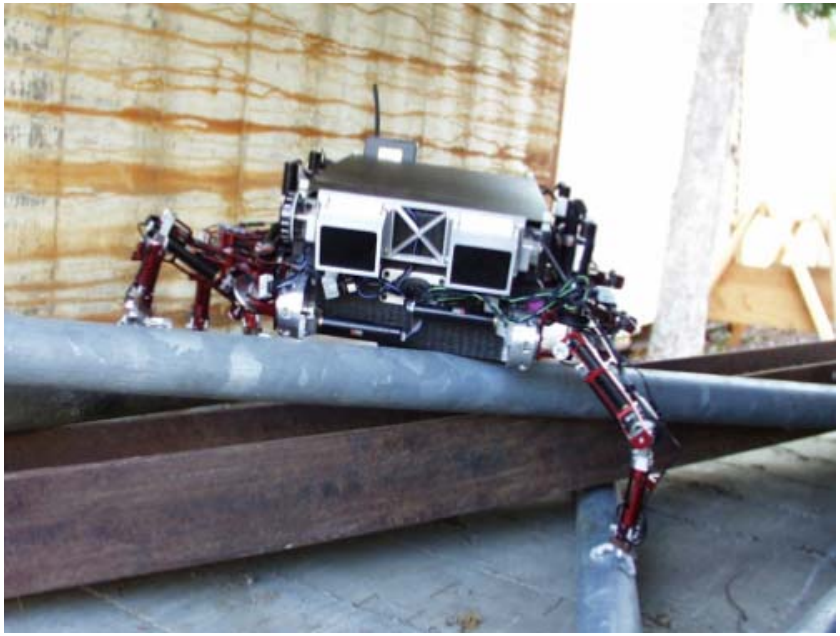
- Creating robots that mimic the shape and performance of biological creatures has always been a highly desirable engineering objective.
- The entertainment and toy industries are greatly benefiting from advancement in this technology.
  - Movies producers are increasingly robots that exhibit realistic behavior.
  - The demonstrated capabilities include creatures that are no longer in existence as in the case of dinosaurs that were emulated in the movie “Jurassic Park”.
  - When visiting toy stores, one can easily see how far technology has progressed in making inexpensive toys that imitate biology.
    - Such store displays include frogs swimming in a fish bowl and dogs walking back and forth. Operating robots that emulate the functions and performance of human or animals involve using capabilities of actuators and mechanisms that depend on state-of-the-art technology.
- Upper-end robots and toys are becoming increasingly sophisticated, allowing them to walk and talk and some robots can be operated autonomously or can be remotely reprogrammed to change their characteristic behavior.
- Robots can make body and facial expressions and exhibit behaviors that are similar to human and animals.
- Such robots can also express and react to human facial and verbal expressions (e.g., MIT’s Kismet)
- As this technology evolves it is becoming more likely that in the future, human-like robots may be developed to perform tasks without human faults of making errors, needing a break, being distracted, or getting tired.
- These robots may be programmed to display moods of happiness, sadness, and others as needed.

Robotics emulating biology – potential concerns

- One may expect to see a day when such robots could become human companions and advisors.
- At such point, biomimetic robots population will increase to possibly become a household “tool” just as the personal computer.
- With the increase in availability of robots as humans property there will a rise in need to protect them as valuable asset possibly requiring equipping them with self-defense.
- Such capability will raise major concern issues related to the limits that will be allowed with regards to their interaction with humans.
- Other potential issue that may rise with the evolution of such robots is the potential copying of humans forming the equivalence of cloning.
- In contrast to the genetic procedure which can take many years to grow a duplicate of the human without ability to control the outcome, the robotic version can potentially be rapidly produced and be programmed to emulate the behavior and response of the original person.
- Aspects of this mimicking will need to be addressed by future generations as the potential unlawful possibilities that may become possible may pose major concerns to law-enforcement agencies.

Legged robots

MACS crawling on a wall using suction cups [Bar-Cohen, 2000].



JPL's Lemur, 6-legged robots, in a staged operation (Courtesy of Brett Kennedy, JPL)

Social and other biological behaviors

- One of the many characteristics of humans and animals is their sociability, i.e., having the ability to express feelings, respond to stimulation, and make independent decisions, actions and reactions.
- Efforts are increasingly being made to imitate such characteristics with robots.
- These robots are being equipped with autonomous operation, the ability to communicate feelings in the form of facial expressions and voices, to react to feelings expressed by humans, to have defense and attack capabilities, as well as many other characteristics that are considered *biological*.
- Generally, many of our behavioral characteristics are learned throughout our life, with some abilities that are genetically coded and improved through our life experience.
- Some animals have some abilities that are far superior to those of humans and these are coded into their genetics.
  - For example, babies of migratory animals begin walking without assistance or guidance minutes after birth.
  - While the baby depends on its mother for milk for survival, it is "equipped" with extensive other abilities that are critical to its survival including seeing, hearing, running, recognizing danger and even taking passive self-defense actions.
- Inspired by these characteristics, robots are increasingly being developed with autonomous operations and programmed with social abilities to interact with human.
- Learning to make realistic robots with social skills can have many important benefits including the understanding of humans' behavior as well as providing a cure to certain phobias.
  - Recent advances in virtual reality and AI are allowing studying and treating patients with such phobias as fear of height, and closed areas.
- Social creatures, including insects and birds, have various approaches for solving difficult computational problems such as discrete optimization.
  - Examples of modeling for optimization include activities in ant colony and the pigeons' seed-picking process.
  - The latter, which is also known as the Particle Swarm optimization algorithm is an analytical tool that is based on the statistical process of seeds picking.
  - This algorithm is considered very effective in evolving hardware and particularly in designing combinational electric circuits.
  - These biologically inspired optimization algorithms are used to solve such problems as vehicle routing and the routing in telecommunication networks.

Social and other biological behaviors

- Operating in a group generally gives social creatures advantages in defense that are unavailable to animals that operate as individuals.
  - Migrant animals move as a herd, warn each other and even jointly defend themselves.
  - Birds fly in formation to help with long distance travel by taking advantage of vortices that are formed by flapping their wings.
  - Lionesses gather in packs to protect their cubs not only from potential enemies but also from other male lions, as lions will kill cubs that are not their own in order to have their own genes entered into the species gene pool.
  - Ants and bees live in a social structure and are able to accomplish extensive tasks because of this behavior.
  - Wolves traveling in packs to hunt have the head of the pack “instruct” the other wolfs who obey the head’s orders while chasing herds or other preys.
    - In some ways, military operations are similar, as the commander in a military operation directs the soldiers and they also “obey the orders” while executing the war strategy that is dictated by the commander.
    - Generally, wolfs have a highly complex social order where every pack has a male leader and all wolves in the pack are aware of their positions through communication with various body postures.
- Roboticists are now considering the use of multiple small robots that can operate in colonies like the ants.
  - Such robots are made capable to operate both as individuals in a cooperative systems and as inter-connectable parts of a large system.
  - These capabilities are far beyond those that can be obtained with an individual robot.

Organic systems using electrically conducting polymers

- Organic electronics, or plastic electronics, is a branch of electronics that deals with conductive polymers.
  - It is called 'organic' electronics because the molecules in the polymer are carbon-based, like the molecules of living things.
  - This is as opposed to traditional electronics which relies on inorganic conductors such as copper or silicon.
- Conductive polymers are lighter, more flexible, and less expensive than inorganic conductors.
  - This makes them a desirable alternative in many applications.
  - It also creates the possibility of new applications that would be impossible using copper or silicon.
  - New applications include smart windows and electronic paper.
- Conductive polymers are expected to play an important role in the emerging science of molecular computing.
- Conductive polymers have a higher resistance and therefore conduct electricity poorly and inefficiently, as compared to inorganic conductors.
- Researchers currently are exploring ways of "doping" organic semiconductors, like melanin, with relatively small amounts of conductive metals to boost conductivity.
- However, for many applications, inorganic conductors will remain the only viable option.

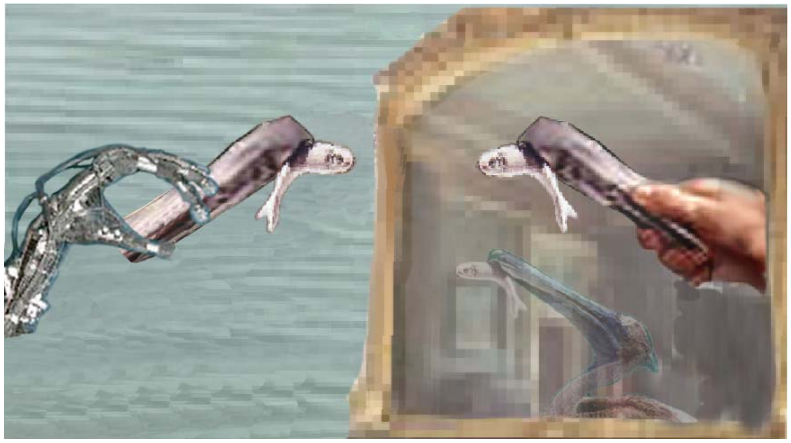
Ref: http://en.wikipedia.org/wiki/Organic_electronics

Organic systems using electrically conducting polymers

- McGinness, Corry, and Proctor reported a high conductivity state in a polyacetylene and the first organic electronic device.
- This was a voltage-controlled switch (1974).
- These researchers further patented batteries, etc. using organic semi-conductive materials. Their original "gadget" is now in the Smithsonian's collection of early electronic devices.
- However, though in a major journal, this early work was lost and went uncredited.
- Consequently, the men principally credited for the discovery and development of conductive organic polymers were Alan J. Heeger, Alan G. MacDiarmid, and Hideki Shirakawa, who were jointly awarded the Nobel Prize in Chemistry in 2000.
- Examples of electrically conductive polymers include polyacetylene: polyaniline: PANI, when doped with a protonic acid; and poly(dioctyl-bithiophene): PDOT.
- Every electrically conductive polymer is conductive due to resonance stabilization and delocalization of pi electrons along entire polymer backbones.

Ref: http://en.wikipedia.org/wiki/Organic_electronics

7. Biomimetics - Summary and future expectations



Biomimetics

Biologically Inspired Technologies

Yoseph Bar-Cohen, JPL

Needs and Challenges

- Better energy sources and more efficient energy utilization
  - Possibly use nature resources with chemical and or photosynthesis to produce required energy
- Sensors that detect in ranges previously unexplored
- Better communication devices
- Components that can be trusted to be fabricated as designed or maybe systems that are designed with superb performance but not strict specs
  - Systems that can be built with imperfect and failure prone components
  - Systems that sense their performance and repair themselves
- Systems that combine smart hardware and software
- Systems that learn to adapt to the environment

The need for efficient systems operation

- Over the course of a day, the body uses 1680 watts doing nothing but sustaining basic functions.
- The best batteries provide 200 watts.

- Over the course of a day, we would need to consume 8.5 kilograms of lithium-ion batteries just to sustain life.
- Biological processes can provide an equivalent amount of power using <0.2-kg olive oil.

Reference: Per Col. Geoffrey Ling, M.D., Ph.D., Program Manager, Defense Sciences Office, in DARPATech 2005

Biology as a model

- Nature has an enormous pool of inventions that passed the harsh test of practicality and durability in changing environment.
- In order to harness the most from nature's inventions it is critical to bridge between the fields of biology and engineering.
- This bridging effort can be a key to turning nature's inventions into engineering capabilities, tools, and mechanisms.
- In order to approach nature in engineering terms it is necessary to sort biological capabilities along technological categories using a top down structure or vise versa.
- Namely, one can take each aspect of the biologically identified characteristics and seek an analogy in terms of an artificial technology.
- The emergence of nano-technologies, miniature highly capable and fast micro-processors, effective power storage, large compact and fast access memory, wireless communication and many others are making the mimicking of nature capabilities significantly more feasible.
- One reason for this is because both natural and artificial structures depend on the same fundamental units of atoms and molecules.

Characteristic similarities of biology and engineering systems

Biology	Engineering	Bioengineering, Biomimetics, Bionics, and Biomechanics
Body	System	Systems with multifunctional materials and structures are developed emulating the capability of biological systems
Skeleton and bones	Structure and support struts	Support structures are part of every human made system. Further, exoskeletons are developed to augment the operation of humans for medical, military and other applications
Brain	Computer	Advances in computers are being made modeling and emulating the operation of the human brain, e.g., the adaptation of the association approach of memory search in the brain to make faster data access
Nerve system	Electric systems and neural networks	Our nervous system is somewhat analogous to electrical systems, especially when it is incorporated with neural networks. The connections of elements in both systems are based on significantly different characteristics.
Intelligence	Artificial Intelligence	There are numerous aspects of artificial intelligence that have been inspired by biology including: Augmented Perception, Augmented Reality, Autonomous Systems, Computational Intelligence, Expert Systems, Fuzzy Logic, Intelligent Control, Learning and Reasoning Systems, Machine Consciousness, Neural Networks, Path Planning, Programming, Task Planning, Simulation, Symbolic Models, etc.
Senses	Sensors	Computer vision, artificial vision, acoustic and ultrasonic technology, radar, and other proximity detectors all have direct biological analogies. However, at their best, the capability of the human-made sensors is nowhere near as good as biosensors
Muscles	Actuators	Electroactive polymers are artificial actuators with very close functional similarity to natural muscles
Electrochemical power generation	Rechargeable batteries	The use of biological materials, namely carbohydrates, fats, and sugars to produce power will offer mechanical systems with enormous advantages
DNA	Computer code	Efforts are being made to develop artificial equivalent of DNA

Characteristics of biomimetic mechanisms

- Multifunctional materials and structures
- High strength configurations
- Just-in-time manufacturing
- Deployable structures
- Hammering without vibration back-propagation
- Nanostructures
- Behavior and cooperative operation
- Mimicking aerodynamic performance
- Mobility
  - Attaching to steep walls and upside down from a ceiling
  - Autonomous locomotion
- Sensors and feedback
- Optimization tools and algorithms
- Machine/human interaction

Turning science fiction into engineering reality

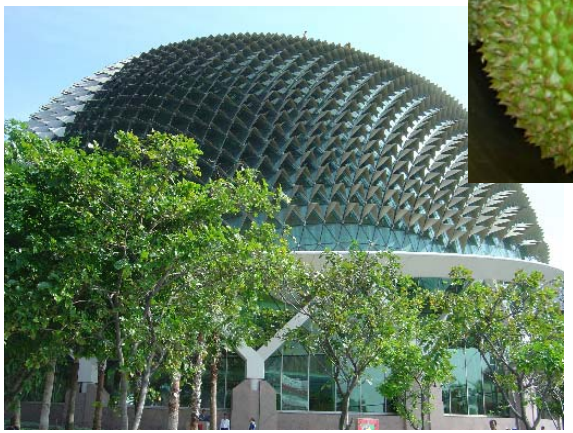
- Biology is filled with solutions and inventions that has been the subject of mimicking and continues to offer enormous potential for human made mechanisms, tools and algorithms.
- Some of the functions that are performed by creatures are far from becoming an engineering reality – For example the octopus' capability to travel through narrow passages significantly smaller than its body cross section.
- Making a robot that can camouflage itself as well as an octopus and defend itself with multiple tentacles using numerous suction cups and poisonous needles offers enormous potential for homeland defense, but it is far from reality.
- Science fiction movies and literature have created a level of expectations for the field of biomimetics and robotics that is far from reality, though these expectations offer creative ideas.
- Employing biologically inspired principles, mobility, sensing and navigation are driving revolutionary capabilities in emerging robots.

Turning science fiction into engineering reality

- Development in biomimetics may lead to a day when intelligent robots could replace dogs, offering unmatched benefits in terms of capability and intellectual support.
  - It may become possible to discuss with robots strategies for stock market investment, obtain advice about a personal problem, or possibly debate philosophical thoughts and politics.
  - One may be able to have the robot read books in any desired language, accent or gender voice, and be able to answer questions about unclear words or sentence in a book as well as provide related information and background.
- The robot may be able to cheer you up, laugh when a funny situation occurs, smell and identify odors, as well as taste food and provide detailed nutrition and health information.
- Being fully autonomous, biomimetic robots would conduct self-diagnostics and go to the selected maintenance facility for periodic checkup and possibly repair themselves as needed.
- Rapid prototyping will enable fast development of this technology as improvements are introduced to the field. While many positive aspect may result from the development of such robots with humanistic capabilities and behavior, negative issues may arise that will require attention.
  - Such issues may include owner liability in case of accident or “misbehavior” of the robot, as well as the potential use of robots for unlawful acts.

Impact of biomimetics on non engineering fields

- Throughout the history of mankind Nature has been an inspiration also to many non-engineering fields.
- Economy greatly mimics biology - in nature, entities compete for energy, while in economy they compete for money
- Engineering and art with biomimetic characteristics are increasingly being integrated in such areas as construction of modern buildings and other structures.
- Examples of the influence of nature on construction are the architectural landmarks that include the Sydney Opera House in Australia and the Esplanade Theater in Singapore.
- The Sydney Opera House has an artistic configuration of sea shells. It was originally designed by the Danish Architect Joern Utzonhas and was opened in 1973.
- The construction of the Esplanade Theater in Singapore was influenced by the durian fruit.
  - In Singapore, this fruit is considered the King of Fruits - it is sweet, spiky and weighs about
  - It is native to Malaysia and Indonesia, green to brown, oblong to round, prickly with strong sharp thorns and emits a strong, distinctive smell that puts most foreigners off and is forbidden from being carried on public transportation such as aircraft and subway.
  - The durian fruit inspired the construction of the Esplanade Theater that was opened in October 2002.
  - This building consists of two domes having the shape of this fruit with durian-like spikes that are used as sun shields. For its shape this theater is also known as the Durians Building.



The need for efficient systems operation

- After billions of years of evolution, nature developed inventions that work, which are appropriate for the intended tasks and that last.
- The evolution of nature led to the introduction of highly effective and power efficient biological mechanisms.
- Failed solutions often led to the extinction of the specific species that became a fossil.
- In its evolution, nature archived its solutions in genes of creatures that make up the terrestrial life around us.
- Imitating nature's mechanisms offers enormous potentials for the improvement of our life and the tools we use.
- Humans have always made efforts to imitate nature and we are increasingly reaching levels of advancement where it becomes significantly easier to mimic biological methods, processes and systems.
- Advances in science and technology are leading to knowledge and capabilities that are multiplying every year.
- These improvements led to capabilities to better understand and implement nature's principles in more complex ways.
- Effectively, we have now significantly better appreciation of nature's capabilities allowing us to employ, extract, copy and adapt its inventions.

The need for efficient systems operation

- Benefits from the study of biomimetics can be seen in many applications, including stronger fiber, multifunctional materials, improved drugs, superior robots, and many others.
- Another aspect of biomimetics is to recognize the importance of protecting species from extinction, lest we lose Nature's solutions that managed to survive, but that we have not yet studied or still don't understand.
- Nature offers a model for us as humans in our efforts to address our needs.
- We can learn manufacturing techniques from animals and plants such as the use of sunlight and simple compounds to produce with no prolusion, biodegradable fibers, ceramics, plastics, and various chemicals.
- Nature has already provided a model for many human-made devices, processes and mechanisms. One can envision the emergence of extremely strong fibers that are woven as the spider does, and ceramics that are shatterproof emulating the pearl.
- Besides providing models, nature can serve as a guide to determine the appropriateness of our innovations in terms of durability, performance, and compatibility.

The need for efficient systems operation

- Biomimetics has many challenges, where the author's armwrestling challenge announced in 1999 has taken the human muscle as a baseline for the development of artificial muscles.
- This is still a challenge even after the competition that was held in 2005, however advances towards making such arms are helping the field of biomimetic greatly.
- The inspiration of nature is expected to continue leading to technology improvements and the impact is expected to be felt in every aspect of our lives.
- Some of the solutions may be considered science-fiction in today's capability, but as we improve our understanding of nature and develop better capabilities this may become a reality that is closer than we think.