TECHNICAL NOTE

Biologically Inspired Intelligent Robots using Artificial Muscles

Y. Bar-Cohen

Jet Propulsion Laboratory/Caltech, 4800 Oak Grove Drive, Pasadena, CA, USA

Introduction

In December 2002, the Japanese company Eamex (Suita City, Osaka, Japan) produced robot fish that swims in a water tank without batteries or a motor (see Figure 1). For power, these robots use an inductive coil that is energized from the top and bottom of the fish tank. Making a floating robot fish may not have been an exciting event, but this one is the first commercial product that used electroactive polymers (EAP) and this marks a major milestone. Because of their functional similarity to natural muscles, EAP materials have earned the name artificial muscles [1].

Electroactive polymers are materials that change shape and size when stimulated by an electric current or voltage. The EAP materials that have been developed so far exhibit low conversion efficiency, are not robust, and there are no standard materials available commercially for consideration in practical applications. In order to transform these materials from the development phase to application as effective actuators, there is a need for an established infrastructure. For this purpose, efforts are underway to develop a comprehensive understanding of EAP materials behaviour, as well as effective processing, shaping and characterization techniques. The technology of artificial muscles is still in its emerging stages but the increased resources, the growing number of investigators conducting research related to EAP, and the improved collaboration among developers, users, and sponsors are leading to a rapid progress.

In 1999, in an effort to promote worldwide development towards the realization of the potential of EAP materials, the author posed an arm-wrestling challenge. A graphic rendering of this challenge is illustrated in Figure 2. In posing this challenge, the author sought to see an EAP-activated robotic arm win against human in a wrestling match to establish a baseline for the implementation of the advances in the development of these materials. While such a challenge was intended to jump-start the research activity in this field, success in wrestling against humans will enable capabilities that are currently considered impossible. It would allow applying EAP materials to improve many aspects of our life, where some of the possibilities include effective implants and smart prosthetics, active clothing, realistic biologically inspired robots and the fabrication of products with unmatched capabilities and dexterity. Decades from now on, we can expect to see EAP materials replacing damaged human muscles, i.e. making 'bionic human.' A remarkable contribution of the EAP field would be to see one day a handicapped person jogging to the grocery store using this technology. Recent advances in understanding the behaviour of EAP materials and the improvement of their efficiency led to the point that the first arm-wrestling competition is planned for 7 March 2005 during the EAP-in-Action Session of the EAPAD Conference [http://ndeaa.jpl.nasa.gov/nasa-nde/lommas/eap/EAP-armwrestling.htm], where three organizations (listed by order of announcement) have already stated their readiness to take part in the competition:

1. SRI International, Menlo Park, CA, USA (currently seeking the necessary funds to develop the required arm in order to compete).
2. Environmental Robots Incorporated (ERI), Albuquerque, NM, USA.
3. Swiss Federal Laboratories for Materials Testing and Research, EMPA, Dubendorf, Switzerland.

Having actuation capability in addition to the other advantages of polymers including lightweight, inexpensiveness, and fracture tolerance all make these materials highly attractive. As polymers, EAP can potentially be configured into almost any conceivable shape and their properties can be tailored to suit a broad range of requirements. Since the early 1990s, new EAP materials have emerged that produce significant shape and size change in response to electrical stimulation [2]. Practitioners of biomimetics are

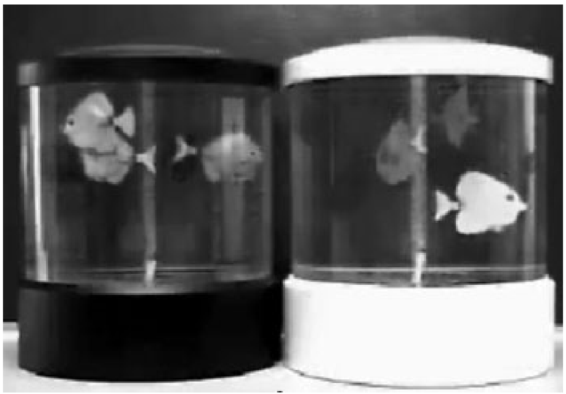

Figure 1: The first EAP-based commercial product – a robot fish (Eamex, Japan)

Figure 2: Grand challenge for the development of EAP-actuated robotics

particularly excited about these materials, as they can be used to mimic the movements of humans and animals [3].

The Types of Available EAP Materials

One of the key aspects of driving mechanisms that emulate biology is the development of actuators that mimic the biological muscles. The potential for such actuators is continuously growing as advances are being made leading to more effective EAP [1]. These materials have functional similarities to biological muscles, including resilience, quiet operation, damage tolerance, and large actuation strains (stretching, contracting or bending). They can potentially provide more life-like aesthetics, vibration and shock dampening, and more flexible actuator configurations. These materials can be used to make mechanical devices and robots with no traditional components like gears, and bearings, which are responsible to their high costs, weight and premature failures.

The advent of the field of EAP can be traced back to an 1880 experiment that was conducted by Roentgen using a rubber-band with fixed end and a mass attached to the free-end, which was charged and discharged [4]. Generally, there are many polymers that exhibit volume or shape change in response to perturbation of the balance between repulsive intermolecular forces, which act to expand the polymer network, and attractive forces that act to shrink it. Repulsive forces are usually electrostatic or hydrophobic in nature, whereas attraction is mediated by hydrogen bonding or van der Waals interactions. The competition between these counteracting forces, and hence the volume or shape change, can be controlled by subtle changes in parameters such as solvent, gel composition, temperature, pH, light, etc. The type of polymers that can be activated by non-electrical means include: chemically activated, shape memory polymers, inflatable structures, including McKibben Muscle, light-activated polymers, magnetically activated polymers, and thermally activated gels (Chapter 1, [1]).

Polymers that are chemically stimulated were discovered over half a century ago when collagen filaments were demonstrated to reversibly contract or expand when dipped in acid or alkali aqueous solutions, respectively [5]. Although relatively little has since been done to exploit such 'chemo-mechanical' actuators, this early work pioneered the development of synthetic polymers that mimic biological muscles. The convenience and practicality of electrical stimulation and technological progress led to a growing interest in EAP materials. Following the 1969 observation of a substantial piezoelectric activity in PVF2 [http://www.ndt.net/article/yosi/yosi.htm], investigators started to examine other polymer systems, and a series of effective materials have emerged. The largest progress in EAP materials development has occurred in the last 10 years, where effective materials that can induce up to 380% strain have emerged [6].

Electroactive polymers can be divided into two major categories based on their activation mechanism including ionic and electronic. The electronic EAP are driven by Coulomb forces and they include: dielectric EAP (shown in Figure 3A), electrostrictive graft elastomers, electrostrictive paper, electro-visco-elastic elastomers, ferroelectric polymers and liquid crystal elastomers (LCE). This type of EAP materials can be made to hold the induced displacement while activated under a DC voltage, allowing them to be considered for robotic applications. These materials have a greater mechanical energy density and they can be operated in air with no major constraints. However, the electronic EAP require a high activation fields (>30 V μm^{-1}) that may be close to the breakdown level. In contrast to the electronic EAP, ionic

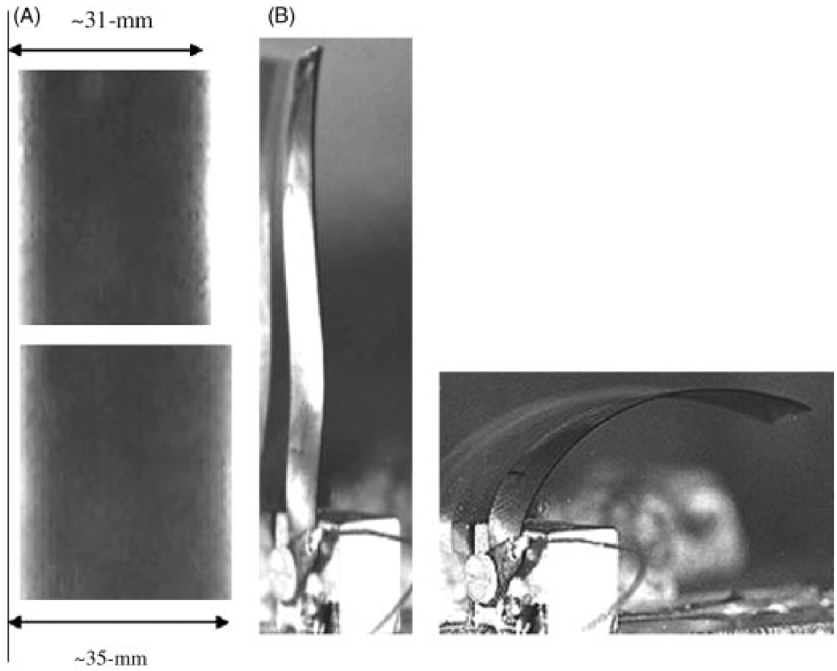

Figure 3: Examples of EAP materials in relaxed and activated states. (A) Dielectric EAP in relaxed (top) and activated states (bottom); (B) IPMC in relaxed (left) and activated states (right)

EAP are materials that involve mobility or diffusion of ions and they consist of two electrodes and an electrolyte. The activation of the ionic EAP can be made by as low as 1–2 V and mostly a bending displacement is induced. The ionic EAP include carbon nanotubes (CNT), conductive polymers (CP), electrorheological fluids (ERF), ionic polymer gels (IPG) and ionic polymer metallic composite (IPMC) (shown in Figure 3B). Their disadvantages are the need to maintain wetness and they pose difficulties to sustain constant displacement under activation of a DC voltage (except for conductive polymers).

The induced displacement of both the electronic and ionic EAP materials can be designed geometrically to bend, stretch or contract. Any of the existing EAP materials can be made to bend with a significant bending response, offering an actuator with an easy-to-see reaction. However, bending actuators have relatively limited applications because of the low force or torque that can be induced. One important question, which has been asked by new users or researchers/engineers who are newcomers to this field, is the need to know where they can get these materials. This issue of unavailability of commercial EAP materials is dampening the rate of progress in the field of EAP. To help potential users, the author has established a website that describes how to make the various EAP materials [http://ndeaa.jpl.nasa.gov/nasa-nde/lommas/eap/EAP-recipe.htm]. Furthermore, the author compiled inputs from companies that make EAP materials, prototype devices or provide EAP-related processes and services. The inputs were compiled into a handy table that is posted on one of the links of the WW-EAP webhub: http://ndeaa.jpl.nasa.gov/nasa-nde/lommas/eap/EAP-material-n-products.htm.

Biomimetic Robots

The field of robotics has evolved from automation satisfying the desire to emulate the biological characteristics of manipulation and mobility. In recent years, significant advances have been made in robotics, artificial intelligence and others fields allowing for making sophisticated biologically inspired robots [3]. Using these advances, scientists and engineers are increasingly reverse engineering many animals' performance characteristics. Biologically inspired robotics is a subset of the interdisciplinary field of biomimetics. Technology progress resulted in machines that can recognize facial expressions, understand speech, and perform mobility very similar to living creatures including walking, hopping, and swimming. The emergence of EAP materials has opened a new range of possibilities taking advantage of the remarkably functional characteristic similar to biological muscles.

Making creatures that behave like the biological model is a standard procedure for the animatronics industry that graphically animates the appearance and behaviour of such creatures quite well. However, engineering such biomimetic intelligent creatures as realistic robots is still a challenge because of the need to meet physical and technological constraints. Making simple tasks such as hopping and landing safely without risking damage to the mechanism, or making body and facial expression of joy and excitement, which are very easy tasks for human and animals, are extremely complex to engineer. The use of artificial intelligence, effective artificial muscles and other biomimetic technologies are increasingly contributing to the possibility of making realistically looking and behaving robots. At the current pace of development, it is becoming more realistic to expect the inevitability of the development of machines as our peers.

This article focuses only on the topic of artificial muscles, their state-of-the-art and the challenges in using them to make fully functional biomimetic intelligent robots. While the engineering challenges are very interesting to address there are also fundamental issues that need attention but they will not be covered herein. Some of these issues include self-defence, rituals for interactions with humans, controlled termination, definition of standard body language for such robots as well as many others. There is already an extensive heritage of making robots and toys that look and operate similar to biological creatures and models for such robots are greatly inspired by science fiction (e.g. books, movies, toys and animatronics). Generally, the perception and expectations are far beyond the reach of current engineering capabilities that are constrained by laws of physics and the state-of-the-art technology.

Biology and Nature as Inspiring Models

Evolution over millions of years in nature led to the introduction of highly effective and power efficient biological mechanisms. Imitating these mechanisms offers enormous potentials for the improvement of our life and the tools we use. Humans have always made efforts to imitate nature but the improvement in technology has made it easier to make such adaptation.

The wheel has been one of the most important inventions of humans, allowing them to traverse great distances and perform tasks that would have been otherwise impossible within the lifetime of a single human being. While wheel locomotion mechanisms allow great distances and speeds to be reached, wheeled vehicles are subjected to great limitations with regards to traversing complex terrain with 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. Making miniature devices that can fly like a dragonfly; adhere to walls like gecko; adapt the texture, patterns and shape of the surrounding as the octopus (it can reconfigure its body to pass through very narrow tubing); process complex 3D images in real time; recycle mobility power for highly efficient operation and locomotion; self-replicate; self-grow using surrounding resources; chemically generate and store energy; and many other capabilities are some of the areas that biology offers a model for science and engineering inspiration. While many aspects of biology are still beyond our understanding and capability, significant progress has been made. Adapting the mechanisms of nature may be more effective to make by mimicking the functional capability rather than fully copying the mechanisms. The airplane is one such example, where humans' attempting to fly like birds over many centuries failed as long as they simply tried to copy nature. There is no doubt that human-made machines have significantly surpassed biology in flying way higher, faster and per form functions that are far beyond any creature's capability.

Biomimetic Robots using EAP

Mimicking nature would significantly expand the functionality of robots allowing performance of tasks that are currently impossible. As technology evolves, a great number of biologically inspired robots actuated by EAP materials emulating biological creatures is expected to emerge. To promote the development of effective EAP actuators, which could impact future robotics, toys, and animatronics, two platforms were developed (see Figure 4). These platforms are available at the author's laboratory in JPL and they include an Android head that can make facial expressions and a robotic hand with movable joints. At present, conventional electric motors are producing the required facial expressions of the Android. Once effective EAP materials are chosen, they will be modelled into the control system in terms of surface shape modifications and control instructions for the creation of the desired facial expressions. Furthermore, the robotic hand is equipped with tendons and sensors for the operation of the various joints,

Figure 4: An android head and a robotic hand that are serving as biomimetic platforms for the development of artificial muscles. *Note:* This photo was taken at JPL where the head was sculptured and instrumented by David Hanson, University of Texas, Dallas, and the hand was made by Graham Whiteley, Sheffield Hallam U., UK

mimicking the human hand. The index finger of this hand is currently being driven by conventional motors in order to establish a baseline and these tendons would be substituted by EAP when such materials are developed as effective actuators.

The field of artificial muscles offers many important possibilities for the engineering of robots. The ease of producing EAP in various shapes and configurations can be exploited using such methods as stereolithography and ink-jet processing techniques. Potentially, a polymer can be dissolved in a volatile solvent and ejected drop-by-drop onto various substrates. Such rapid prototyping processing methods may lead to mass-produced robots in full 3D details including the actuators, allowing rapid prototyping and quick transition from concept to complete production [2]. While such capabilities are expected to significantly change future robots, additional effort is needed to develop robust and effective polymer-based actuators.

Biologically Inspired Robots

The evolution in capabilities that are inspired by biology has increased to a level where more sophisticated and demanding fields, such as space science, are considering the use of such robots. At JPL, a six-legged robot is currently being developed for consideration in future missions to planets such as Mars. Such robots include the limbed excursion mobile utility robot

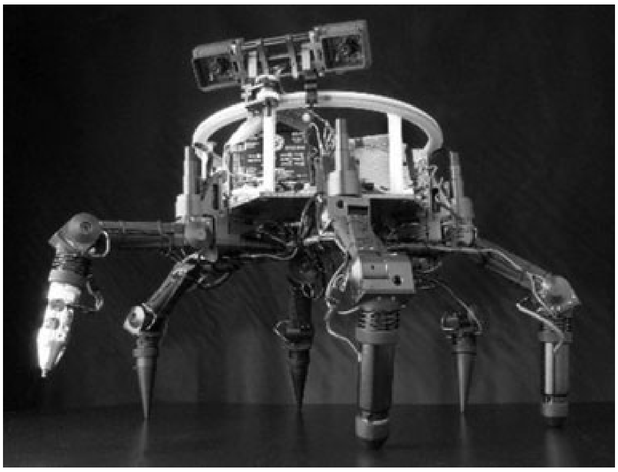

Figure 5: A new class of multi-limbed robots called limbed excursion mobile utility robot (LEMUR) is under development at JPL (courtesy Brett Kennedy, JPL)

(LEMUR). This type of robot would potentially perform mobility in complex terrains, sample acquisition and analysis, and many other functions that are attributed to legged animals including grasping and object manipulation. This evolution may potentially lead to the use of life-like robots in future NASA missions which involve landing on various planets including Mars. The details of such future missions may be designed as a plot, commonly used in entertainment shows rather than conventional mission plans of a rover moving in a terrain and performing simple autonomous tasks. Equipped with multi-functional tools and multiple cameras, the LEMUR robots are intended to inspect and maintain installations beyond humanity's easy reach in space with the ability to operate in harsh planetary environments that are hazardous to humans. This spider look-alike robot has six legs, each of which has interchangeable end-effectors to perform the required mission (see Figure 5). The axis-symmetric layout is a lot like a starfish or octopus, and it has a panning camera system that allows omni-directional movement and manipulation operations.

Concluding Remarks

Technologies that allow developing biologically inspired system are increasingly emerging allowing for the development of robots that can walk, hop, swim, dive, crawl, etc. Making robots that are actuated by artificial muscles and controlled by artificial intelligence would enable engineering reality that used to be considered science fiction. Using effective EAP actuators to mimic nature would immensely expand the functionality of robots that are currently available. Making such robots capable of understanding and expressing voice and body language would increase the probability of seeing them as social partners than machines or tools. As the technology advances are made, it is more realistic to expect that biomimetic robots will become commonplace in our future environment. It will be increasingly difficult to distinguish them from organic creatures, unless intentionally designed to be fanciful. As we are inspired by biology to improve our lives we will increasingly be faced with challenges to such implementations. A key to the development of such robots is the use of actuators that mimic muscles, where electroactive polymers (EAP) have emerged with this potential. A series of new artificial muscle materials were developed while the technology infrastructure is being established towards making more efficient material and design effective mechanism. The author's arm-wrestling challenge having a match between EAP-actuated robots and a human opponent highlights the potential of this technology. This match is planned for next year and success of a robot against human opponent will lead to a new era, both in making realistic biomimetic robots and implementing engineering designs that are currently considered science fiction.

ACKNOWLEDGEMENTS

Research reported in this manuscript was partially conducted at the Jet Propulsion Laboratory (JPL), California Institute of Technology, under a contract with National Aeronautics and Space Administration (NASA).

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