Directions for development of the field of Electroactive Polymer (EAP)

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Abstract
In last few years, the rate of development and advances in the field of EAP has accelerated significantly and it is increasingly getting closer to the point of finding them used in commercial products. Substantial development has been reported in the understanding of their drive mechanisms and the parameters that control their electro-activation behavior. Further, efforts are being made to develop mass production techniques with greatly improved actuation capability and operation durability. The recent efforts to develop energy harvesting techniques, haptic interfacing (including refreshable braille displays), and toys are further increasing the likelihood of finding niches for these materials. In this paper, the author sought to examine the potential directions for the future development of the field of EAP in relation to the state-of-the-art.

Keywords: EAP, actuators, Electroactive polymers, Biomimetics, Biologically inspired technologies, Robotics

1.0 Introduction

Electroactive polymers (EAP) have reached the level of advances that among scientists and engineers worldwide they are quite well known electro-actuation materials [Bar-Cohen, 2011]. Also, their moniker "artificial muscles" is increasingly becoming a household name. Being polymers, they posses many advantages including easy to process and mass produce, inherently lightweight, and mechanically flexible making them highly attractive actuation materials. The convenience and the practicality of stimulating electroactive polymers (EAP) and the recent years significant response improvements made them the most preferred type among the mechanically responsive polymers [Bar-Cohen, 2004]. Also, the capability of some of the EAP materials to convert mechanical strain to electrical signal, which is the reverse to actuation, makes them useful as sensors and for energy harvesting applications. Today, there are many EAP materials that are widely known, and as the author grouped them they are divided into: *field activated* (originally he named them *electronic)* and *ionic* [Bar-Cohen, 2004].

In their current state, EAP materials are still considered to be emerging ones that need greater scientific and engineering advancements and significant efforts are being made to turn them to actuators-of-choice. These efforts involve improving the understanding of the basic principles that drive them in order to establish effective computational chemistry models, comprehensive material science, electro-mechanical analytical tools and material processing techniques. To maximize the actuation capability and operation durability, effective processing techniques are being developed for their fabrication, shaping, and electroding. Methods of reliably characterizing the response are being developed and databases [Madden, 2010] are being established. To bring these materials to the level of application to daily used products necessitates finding niche that addresses critical needs. The majority of the applications that are being considered for EAP materials are focused on making actuators and related mechanisms. Specific applications that are being investigated include making manipulators, haptic devices, mobile mechanisms, electro-active functional systems and others.

Using EAP material it is potentially feasible to mimic many biological mechanisms allowing benefiting from the numerous capabilities that resulted from nature's evolution [Bar-Cohen, 2005; Bar-Cohen and Hanson, 2009; Bar-Cohen, 2011]. EAP materials are widely being considered for biologically inspired, i.e., biomimetic, applications including some that once were considered possible only in the realm of science fiction books and movies. The potential applications range in scale from nano and micro (e.g., viruses and bacteria) to macro and mega (e.g. our life scale, elephants, and whales). Effectively, the constraints that human engineers are facing are quite similar to those that nature is dealing with in addressing its challenges including the need to maximize the functionality of the biological systems design using minimal resources (e.g., materials, energy, cost, etc.). Several novel applications of EAP materials as actuators were already demonstrated including robot fish, miniature gripper, loudspeaker, catheter steering element, haptic interface, active braille display and dust-wiper. Other applications that are considered include assistive walking, slithering robots, facial animatronics and even eyelid assistor. The impressive advances in improving their actuation strain capability are attracting the attention of engineers and scientists from many different disciplines. As we making progress in the field, it would be nice to see the directions that the technology could be heading and this paper is seeking a visionary outlook for the field.

2.0 Current and potential applications

In recent years, there has been significant progress toward making practical EAP actuators and commercial products. Increasing number of companies are investigating applications for various markets including zoom lens of cellular phones, valves, energy harvesting, pumps, robot-fish, haptic interfaces and active Braille displays. EAP actuators offer many important capabilities for engineering biomimetic mechanisms and devices [Bar-Cohen, 2004; Bar-Cohen, 2011]. The flying capability of the dragonfly and the hummingbird (**Figure 1**) is quite impressive allowing this insect and bird, respectively, to perform such superb capabilities as hovering, flying backward and surgically reaching their targets. The ability to move a wing structure using a light weight actuator that does not require high power may be possible to achieve via an EAP actuator. The EAP capabilities that are currently being developed are described in the following sub-sections.

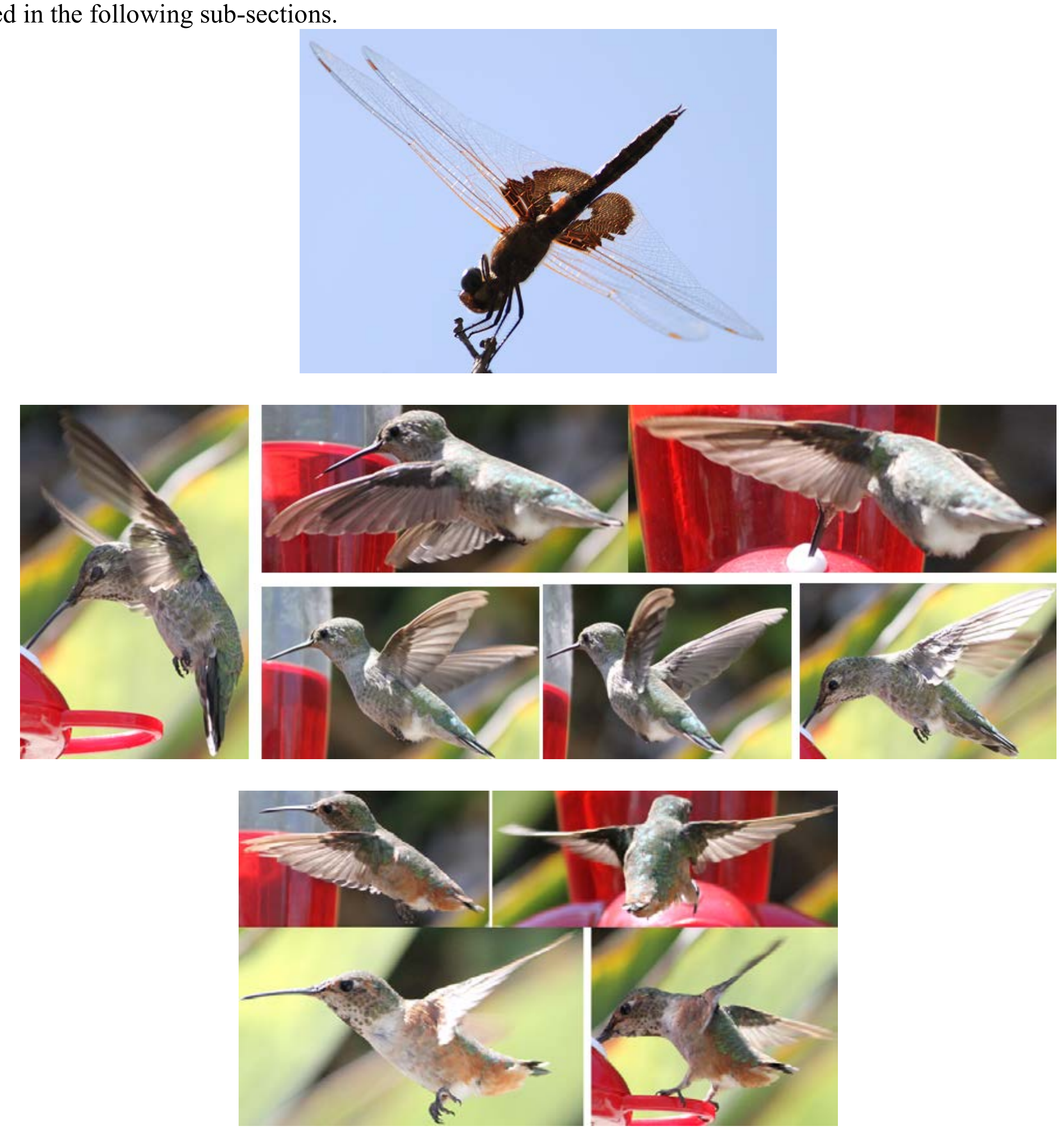

Figure 1: The dragonfly and the hummingbird are very capable flyers. The photos that are showing the hummingbird in various wing positions illustrate the enormous maneuverability and dexterity of its wing.

2.1 Generic actuators

Mechanisms are driven by actuators that move components and elements including for example a manipulator arm or moving the whole body of the system as in the case of a robot. There are many mechanisms that require miniature actuators that are lightweight and use low power. Electroactive ceramic actuators (for example, piezoelectric and electrostrictive) are effective, compact actuation materials and they are be used to replace electromagnetic motors. However, while these materials are capable of delivering large forces, piezoelectric actuators produce a relatively small displacement on the order of magnitude of fraction of a percent. For many years, it was known that certain types of polymers can change shape in response to electrical stimulation, however, initially these materials produced only a relatively small strain (stretching, contracting, or bending). Since the beginning of the 1990s, new electroactive polymers (EAP) have emerged that exhibit large strains and they led to a great paradigm change with regards to their capability. The unique properties of these materials are making them highly attractive actuators and, increasingly, engineers are able to develop EAP actuated mechanisms that were previously imaginable only in science fiction.

2.2 Biomimetic robots

Effective EAP can be used to produce biomimetic robots that perform tasks which are impossible with existing capabilities [Bar-Cohen and Breazeal, 2003, Bar-Cohen, 2005; Bar-Cohen and Hanson, 2009; Bar-Cohen, 2011]. Further, engineers may be able to come up with capabilities that are far superior to biological creatures since they are not constrained by evolution or survival needs. Flight is an example of the success of making biologically inspired technology – airplanes are capable of flying faster, far higher, carry more weight, and operate in significantly more difficult conditions than any existing flying creature on Earth. One may produce such devices as artificial bugs that are capable of combinations of capabilities including walking, swimming, hopping, crawling, and digging. For example, the author and his research team constructed a miniature robotic arm that was lifted by a rolled dielectric elastomer EAP as a linear actuator and was equipped with 4-fingers gripper [Bar-Cohen, 2004]. The linear actuator was used to raise and lower a graphite/epoxy rod that served as a simplistic representation of a robotic arm. The gripper (**Figure 2**) consisted of IPMC strips that act as fingers having hooks at the bottom of the strips mimicking the function of fingernails. As shown in **Figure 2**, this gripper grabbed rocks similar to a human hand. Other examples include robot designs that were developed by scientists at SRI International including the FLEX that is considered the first self-contained walking robot that is driven by EAP. This robot is loosely based on the walking gaits of a cockroach and each of its six legs used two dielectric elastomer actuators to move up and down as well as back and forth. Actuating its legs at frequencies of up to 10 Hz allowed the FLEX robot to move at speeds that are greater than 12 cm/s [Kornbluh et al., 2004].

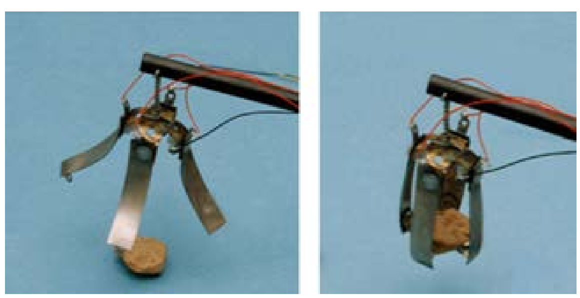

Figure 2: 4-finger EAP gripper lifting a rock.

2.3 Medical applications

Success in applying EAP materials to operate internal organs inside a human body can make tremendous impact on improving the life of many humans. Applications of EAP to the field of medicine were done by many researchers including the use for operating medically related mechanism and devices with biomimetic characteristics. Examples include catheter steering mechanism [Della Santa, et al., 1996], vein connectors for repair after surgery and smart prosthetics [Herr and Kornbluh, 2004]. EAP materials offer the potential of biocompatibility but they need to meet the stringent health safety and reliability requirements for operating inside or adjacent to the human body. At present, the dielectric elastomer EAP materials are finding the most practical applicable since they generate the largest actuation forces and strains and also they have the highest demonstrated reliability. However, the required high voltages poses potential hazard that must be addressed. On the other hand, while the ionic EAP group has the advantage of very low voltage activation, their being chemically active requires the use of effective sealing to protect of the internal organs and avoiding contamination of the ionic content, which causes loss of performance efficiency.

The use of robotics in medical applications is increasingly contributing to significant reduction in mortality after surgery, faster recovery and minimized complications. The de Vinci surgical system is now a standard tool in many hospitals worldwide. Unfortunately, for conducting delicate surgical procedures in such organs as the brain, the current systems are quite large. One may consider a minimally-invasive robotic surgical device that has an octopus-configuration with multiple degrees-of-freedom tentacles equipped with various tools. EAP can be used to actuate the joints and in parallel take advantage of the capability of Electro-Rheological Fluids (ERF) to become highly viscous under electrical excitation. This property would allow controlling the rigidity of the tentacles as well as provide haptic interfacing to surgeons in the form of tactile feeling [Fisch et al., 2003; Bar-Cohen 2004]. An illustration of such a futuristic concept is shown in **Figure 3** [Bar-Cohen. 2005].

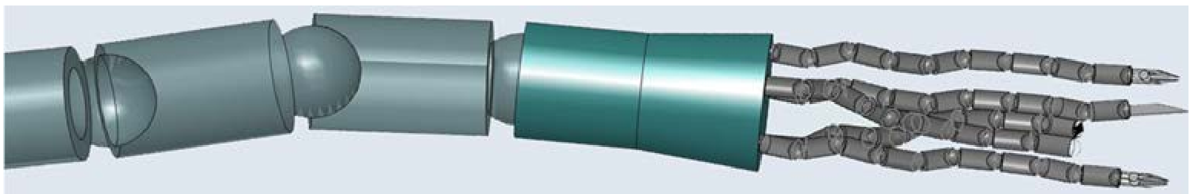

Figure 3: A graphic view of a futuristic octopus-configured catheter for surgical applications.

Activation of the eyelid to enable blinking is an application for EAP that is currently being under development by surgeons at the University of California at Davis. Generally, the involuntary eye blinking is a crucial function that lubricates and cleans the eye and it is controlled by a cranial nerve. Also, persons with this impairment have difficulties keeping the lid closed when lying down to sleep. The use of dielectric elastomers as actuators of the eyelid was recently demonstrated [Senders, 2010], where a sling shape structure was activated by dielectric elastomer EAP produced by SRI International. This mechanism is being developed to treat patients who sustained a stroke, accident, or combat injuries that caused lose of the ability to blink. A control package that is similar to the electronic pacemaker could be used to activate this mechanism. The sling would be attached to the bone around the eye and a small battery hidden in a natural hollow in the temple can be used to power the actuator. The prototype of the developed mechanism has been tested successfully on cadavers and is expected to be tested on real patients in a number of years [Chapter 6 in Bar-Cohen, 2011].

Important capabilities for medical applications can be enabled when interfacing human and machine to complement or substitute our senses. A number of such interfaces were investigated and the most significance work is the interfacing of machines and the human brain. A development by scientists at Duke University [Mussa-Ivaldi, 2000; Wessberg et al., 2000], Caltech, MIT, Brown University, and many other research institutes enabled this possibility. For this purpose, electrodes were connected to the brain of a monkey, and, using brain waves, a monkey operated a robotic arm. Recent development under the DRAPA program developing smart prosthetic arms led to the use of the severed nerves of patients to articulate artificial arms. If EAP actuated robotic arms are developed with sufficient strength and dexterity to function as effective prosthetics then this development by neurologists would help disabled people greatly. Using such haptic interfacing capability to control prosthetics would require feedback to allow the human user to “feel” the artificial limbs. The required feedback can be provided with the aid of tactile sensors [Carpi et al., 2009], and other interfacing mechanisms.

2.4 Full page refreshable braille displays

EAP materials offer significant potential for the development of full page refreshable braille displays [Bar-Cohen, 2004; Chapter 7 in Bar-Cohen 2011]. These materials potentially allow for packing many actuators in a small area without interferences. The author pioneered these efforts with the concept that he documented in 1998 [Bar-Cohen, 1998] after being inspired by the presence of visually impaired that coincidently held a convention at a hotel in Washington DC were he stayed. His concept is based using an EAP actuator array made of a Field-Activated EAP where an electric field in the crossing section of rows and columns electrode strips on the opposite sides of an EAP film are activated individually. Each of the electrodes crossing forms an actuation element and is mounted with a braille dot that is lowered by applying voltage across the thickness of the selected elements. Since 2003, other researchers have started reporting the development of EAP based refreshable braille displays. Nine different mechanisms were already reported and their developers include investigators from Wollongong University jointly with Quantum Technologies, Sydney, Australia [Spinks and Wallace, 2009]; Harbin Institute of Technology, China

[Leng and Lan, 2010]; Darmstadt University of Technology: Germany [Matysek et al., 2009]; the University of Tokyo, Tokyo, and the National Institute of Advanced Industrial Science and Technology (AIST), Osaka, Japan [Kato et al., 2007]; Sungkyunkwan University, South Korea [Choi et al., 2009]; as well as Penn State University [Ren et al., 2008], SRI International [Heydt and Chhokar, 2003], Carolina State University [di Spigna, et al., 2009] and UCLA jointly with NASA Ames [Yu et al. 2009] in the USA. These developers used conducting polymers, dielectric elastomers, ferroelectric, IPMC, PVDF, and bistable electroactive polymer (BSEP). Their EAP actuators move levers, rolled film over pre-strained spring, bimorph configuration, multi-layered array, a diaphragm with spring backed elements and pressurized diaphragm elements.

While the developed displays showed a performance that is close to the required specifications, there are still challenges that prevent them from being made as a commercial product [Chapter 7 in Bar-Cohen 2011]. These include the insufficient force in the case of IPMC as well as the short cycling life of the conducting polymers. Also, there are issues related to their reliable operation and limitations in mass production. Advances in developing more effective EAP materials and processing techniques may lead to practical low cost compact refreshable braille displays.

In order to provide a forum for communicating the unique possibilities that EAP actuators offer haptic/tactile interfaces, a special Session of the SPIE 2010 EAPAD Conference was dedicated to this topic, and several related demos were presented at its EAP-in-Action Session.

2.5 Toys and games

Toys and games are products that do not require extensive product durability compared to other industrial ones. Therefore, the application of EAP to actuate toys and games offers an important avenue for the commercialization of such actuators. The use of EAP may allow quick turning of concepts to products and success of few products can help raise enormous revenues to support follow-on development of other applications. The development of such EAP driven devices has already begun and an example includes the efforts at the Auckland Bioengineering Institute's Biomimetics Lab, New Zealand. Their game involves making a ball continuously rotate on a round Plexiglas plate where the ball wobbles forward and backward and a steady control of the plate action by the player allows maintaining rotation [Chapter 6 in Bar-Cohen, 2011]. The player needs to maintain the rotation of the ball in one direction and it is an example of the novel possibilities that EAP actuators offer.

2.6 Dielectric Elastomer Switches (DES)

Operating EAP as smart actuators that emulate biological muscles requires driving them with a distributed network of intelligence and feedback capabilities. Recently, the Auckland Bioengineering Institute's Biomimetics Lab, New Zealand, [O'Brien e al., 2010] reported the integration of intrinsic sensor, control, and driver circuitry into dielectric elastomer EAP. This success brings these artificial muscles closer to the natural analogues, where the piezo-resistive behavior of dielectric elastomer devices was exploited by developing a switching material based on carbon loaded silicone grease to create dielectric elastomer switches (DES). Potential applications may include devices with many degree-of-freedom such as robotic heart, artificial intestine, and manipulators; wearable assistive devices; and ultimately electro-mechanical computers. The fundamental requirements for making a digital computation using DES were demonstrated experimentally in a compliant electromechanical NAND (logical "Not AND") gates and oscillator circuits. These switches are handled as electromechanical relays, hybrid devices combining analogue and digital processing and this approach is expected to reduce the need for bulky and rigid external circuitry. Also, these switches may provide simple distributed intelligence as required to produce soft, biologically inspired networks of actuators.

2.7 Space applications

Generally, space applications are among the most demanding in terms of the harshness of the operating conditions (extreme temperatures, high pressure or vacuum) and they require very high reliability and durability that are beyond the capability of the existing EAP materials. Another challenge for producers of EAP to make these materials applicable for future NASA mission is the need for large scale actuators in the form of films, fibers and others. The required dimensions can be as large as several meters or kilometers possibly producing large gossamer structures such as antennas, solar sails, and various large optical components. Making biomimetic capabilities using EAP material will potentially allow NASA and other space agencies to conduct missions with capabilities that today they are in the realm of science fiction.

Under the author's lead, a NASA study took place between 1995 and 1999 with the objective of improving the understanding and practicality of EAP materials and to identify planetary applications. One of the devices that were developed was a miniature dust wiper for the Nanorover's optical/IR window of the MUSES-CN mission. An

IPMC actuator was used to bend a miniature lightweight (0.1-g) blade that consists of a gold-plated fiberglass brush. To repel dust the blade was subjected to high voltage (1–2 KV) while scanning the surface. The MUSES-CN mission itself was cancelled due to budget constraints but the publicity that resulted from the related NASA Press Release gave the field of EAP important visibility among the science and engineering community and the general public.

3.0 The armwrestling challenge – the capability indicator

The armwrestling challenge that was posed by the author in 1999 [http://ndeaa.jpl.nasa.gov/nasa-nde/lommas/eap/EAP-armwrestling.htm] in an effort to promote worldwide development towards realizing the potential of EAP materials is still not met. This challenge consists of having an EAP activated robotic arm win against human in a wrestling match and the icon of the challenge is shown in **Figure 4**. Choosing to focus on armwrestling with human was done in order to have the human muscles as a baseline for performance comparison. Success will allow using EAP materials to improve many aspects of our life. The first armwrestling match with a human was held on March 7, 2005 [Bar-Cohen, 2005] and the human representative, 17-year old high school female student, won against all the three robotic arms that participated. This was followed with the 2nd contest where, rather than wrestling with a human opponent, the arms performance was measured and the results were compared to the same student.

Figure 4: The icon of the grand challenge for the development of EAP actuated robotics.

4.0 Challenges, trend and potential development

EAP materials that generate large strains and improved actuation forces are increasingly emerging making these materials highly attractive for many applications. Their operational similarity to biological muscles, including resilience, damage tolerance, and ability to induce large actuation strains makes them unique compared to other electroactive materials. Using EAP as actuators involves many challenges and advancing the materials to a mature state necessitates larger actuation forces, electromechanical conversion efficiency, and operation lifetime. Also, there is a need to address the unique requirements of producing and testing practical EAP actuators including:

- There is limited availability of low cost EAP materials in commercial quantities. These materials in actuator forms are still custom made and it is essential to have mass produced EAP actuators.
- For making EAP standard engineering materials it is essential to have established formal database and standard test procedures
- Even though EAP materials can be used in their current form, their actuation force and energy conversion efficiency are low for many applications.
- The lifetime and reliability of many of the available EAP materials is still limited.
- To match the capabilities of biological systems it would essential to establish scaling capability.
- EAP materials need to have superior capability over alternative actuation technologies and, preferably, enable a niche application.

Addressing these challenges requires further advances and multidisciplinary cooperation among experts from various fields including chemists, materials scientist, roboticists, computer and electronic engineers, etc. It is necessary to develop a comprehensive material science, as well as effective electro-mechanics analytical tools and material processing techniques. Researchers are increasingly making improvements in the various related areas including a better understanding of the operation mechanism of the various EAP material types. The processes of synthesizing, fabricating, electroding, shaping and handling are being refined to maximize the actuation capability and durability. Methods of reliably characterizing the response of these materials are being developed and efforts are being made to establish databases with documented material properties to support engineers that are considering the use of these materials. It is quite encouraging to see the growing number of researchers and engineers who are pursuing career in EAP related disciplines.

5.0 Acknowledgement

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