EAP as Artificial Muscles – Progress and Challenges

Yoseph Bar-Cohen
Jet Propulsion Laboratory/Caltech
4800 Oak Grove Drive, M/S 82-105, Pasadena, CA 91109, USA
e-mail: yosi@jpl.nasa.gov Web: http://ndeaa.jpl.nasa.gov

ABSTRACT

During the last decade and a half new polymers have emerged that respond to electrical stimulation with a significant shape or size change. This capability of electroactive polymer (EAP) materials is attracting the attention of engineers and scientists from many different disciplines. Practitioners in biomimetics are particularly excited about these materials since the artificial muscle aspect of EAPs can be applied to mimic the movements of animals and insects. In the foreseeable future, robotic mechanisms actuated by EAP will enable engineers to create devices previously imaginable only in science fiction. Last year, significant accomplishments were reported include the emergence of the first commercial product and the possibility that an arm can be made with EAP actuators having the potential of winning a wrestling match with human. As such major accomplishments continue to be reported it is interesting to review the progress and provide a prospective regarding the development since the first EAPAD conference in 1999. This manuscript covers the progress in the field of EAP and the challenges that are being addressed.

Keywords: EAP, Artificial Muscles, Armwrestling, actuators, biomimetics

1. INTRODUCTION

The emergence of polymers that respond to electrical stimulation with a significant shape or size change has added greatly to the list of desirable properties of polymers [Bar-Cohen, 2001 and 2004]. The large strain response of EAP materials is increasingly attracting the attention of engineers and scientists from many different disciplines who are seeking novel applications. Since EAP materials operate similar to biological muscles, they have earned the popular name "artificial muscles." Experts in biomimetics are particularly excited about these materials since they can be applied to mimic the movements of biological creatures [Bar-Cohen and Breazeal, 2003; and Bar-Cohen, 2004a]. Using this capability, EAP actuated robotic mechanisms are enabling engineers to create devices that were previously only imaginable in science fiction. One such commercial product has already emerged in Dec. 2002 is a form of a Fish-Robot (Eamex, Japan). An example of this Fish-Robot is shown in Figure 1. It swims without batteries or a motor and it uses EAP materials that simply bend upon stimulation. For power it uses inductive coils that are energized from the top and bottom of the fish tank. This fish represents a major milestone for the field, as it is the first reported commercial product to use electroactive polymer actuators.

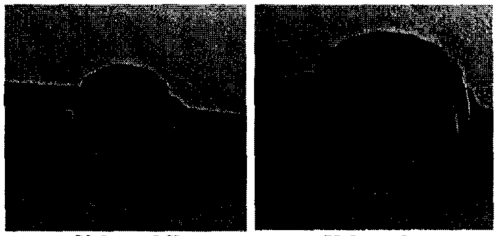
For several decades, it has been known that certain types of polymers can change shape in response to electrical stimulation. Initially, these EAP materials produced a relatively small strain. Since the beginning of the 1990s, a growing number of new EAP materials are emerging with a large strain response to electrical stimulation [Bar-Cohen, 2001 and 2004]. The materials that have emerged were divided by the author into two major groups, including ionic and electronic EAP, and examples of the response of these materials are shown in Figs. 2 and 3, respectively. In Figure 2, a starfish-shaped IPMC (ionomeric polymer-metal composites) is shown to bend significantly. The direction of bending depends on the voltage polarity. In Figure 3, a dielectric EAP is shown with a circular carbon grease electroded area that is activated by an electric field to generate expansion. The expanded elastomer film contracts to the original shape when the electric voltage is turned off. This capability to generate a large strain cannot be matched by alternative active materials such as piezoelectric ceramics and shape memory alloys.

In 1999, in an effort to promote worldwide development towards the realization of the potential of EAP materials the author posed an armwrestling challenge. A graphic rendering of this challenge is illustrated in Figure 4. 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. Success in wrestling against human 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 prosthetics, active clothing, realistic biologically inspired robots as well as fabricating products with unmatched capabilities and dexterity. Recent advances in understanding the behavior of EAP materials and the improvement of their efficiency led to the point where the possibility of EAP actuated arm can win such wrestling match may become feasible in the coming years. The most notable milestone is the recent announcement of scientists from SRI

International, USA, stating that they believe they can build such a robotic arm. To plan the first international arm-wrestling competition efforts are currently underway to consider holding the competition as part of one of the SPIE's Annual International EAPAD (EAP Actuators and Devices) Conferences in San Diego, California, USA.

FIGURE 1: The first commercial EAP product - a fish robot (courtesy of Eamex, Japan)

FIGURE 2: IPMC multi-finger starfish (courtesy of K. Oguro, Osaka National Research Institute, Osaka, Japan).



Voltage Off　　Voltage On

FIGURE 3: Dielectric actuator demonstrated to expand and relax (courtesy of R. Kornbluh and R. Pelrine, SRI International, USA).

FIGURE 4: Grand challenge for the development of EAP actuated robotics.

In recognition of the need for international cooperation among the developers, users, and potential sponsors, the author organized the first EAP conference on March 1–2, 1999, through The International Society for Optical Engineering (SPIE) as part of the Smart Structures and Materials Symposium [Bar-Cohen, 1999]. This conference was held in Newport Beach, California, USA, and was the largest ever on this subject, marking an important milestone. This conference turned the spotlight onto these emerging materials and their potential. Following this success, a Materials Research Society (MRS) conference was initiated to address fundamental issues related to the material science of EAP [Zhang et al., 1999]. In recent years, there has been increasing number of organizations and technical societies who are organizing workshops, meetings and conferences with sessions on EAP. The SPIE's EAPAD conferences are now organized annually and have been steadily growing in number of presentations and attendees. In addition to the conferences, there is a website called the WorldWide EAP (WW-EAP) Webhub that archives related information and links to homepages of EAP research and development facilities worldwide [http://ndeaa.jpl.nasa.gov/nasa-nde/lommas/eap/EAP-web.htm]. Since June 1999, the semi-annual WW-EAP Newsletter has been published with short synopses from authors worldwide providing a snapshot of their advances. This Newsletter is published electronically and its issues are accessible via the above mentioned WW-EAP webhub [http://ndeaa.jpl.nasa.gov/nasa-nde/lommas/eap/WW-EAP-Newsletter.html]. Further, the author edited a reference book on EAP that has been published in 2001 [Bar-Cohen, 2001] with its 2nd edition is expected to be published before the 2004 EAPAD Conference [Bar-Cohen, 2004]. This book provides a comprehensive documented reference, technology user's guide, and tutorial resource, with a vision for the future direction of this field. It covers the field of EAP from all its key aspects, i.e., its full infrastructure, including the available materials, analytical models, processing techniques, and characterization methods.

2. POLYMERS THAT CAN BE STIMULATED TO CHANGE SHAPE OR SIZE

To provide a complete picture one cannot ignore the fact that there are many types of polymers with properties that can be changed by an external stimulation. Some of these polymers exhibit volume or shape change in response to various forms of stimulation. These changes usually result form the perturbation of the balance between repulsive intermolecular forces that act to expand the polymer network, and attraction 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 thus be controlled by subtle changes in parameters such as solvent or gel composition, temperature, pH, light, etc. Activation mechanisms that are not electrical include chemical [Kuhn et al., 1950; and Otero et al., 1995], thermal [Tobushi et al., 1992; and Li et al., 1999], pneumatic [Chou and Hannaford, 1996], optical [van der Veen and Prins, 1971], and magnetic [Zrinyi et al., 1997].

Polymers that are stimulated chemically were discovered more than half a century ago when collagen filaments were demonstrated to reversibly contract or expand when dipped in acid or alkali aqueous solutions, respectively [Katchalsky, 1949]. Even though relatively little has since been done to commercially exploit such "chemo-mechanical" actuators, this early work pioneered the development of synthetic polymers that mimic biological muscles [Steinberg et al., 1966]. However, the convenience and the practicality of electrical stimulation and the recent technical progress have led to a growing interest in EAP materials. Following the 1969 observation of a substantial piezoelectric activity in Poly(vinylidene fluoride) (PVF2) [Bar-Cohen et al., 1996; and Zhang et al., 1998], 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 fifteen years where effective materials that can induce strains of about 300% have emerged [Pelrine et al. 1998].

3. THE EAP TECHNOLOGY INFRASTRUCTURE

As polymers, EAP materials can be easily formed in various shapes, their properties can be engineered, and they can potentially be integrated with micro-sensors to produce smart actuators. Producing practical actuators and mechanisms that are based on EAP requires attention to the critical aspects of these materials. This requires sufficient understanding of the material behavior, ability to optimize the material properties and performance, establish robust actuators with well characterized properties, as well as the development of effective control and design tools. These aspects were identified by the author as the EAP technology infrastructure (see Figure 5) and it defined the roadmap for the technology maturity [Bar-Cohen, 2001]. This effort to develop the infrastructure is multidisciplinary and requires international collaboration.

3.1 Electroactive polymers (EAP) materials

Polymers that exhibit shape change in response to electrical stimulation can be divided into two distinct groups: electronic (driven by electric field or Coulomb forces) and ionic (involving mobility or diffusion of ions). The electronic EAP materials (electrostrictive, electrostatic, piezoelectric, and ferroelectric) require high activation fields (>10 V/μm) close to the breakdown level. However, they can be made to hold the induced displacement under activation of a dc voltage, allowing them to be considered for robotic applications. Also, these materials have a faster response and they can be operated in air with no major constraints. In contrast, ionic EAP materials (gels, polymer-metal composites, conductive polymers, and carbon nanotubes) require drive voltages as low as 1–5 V. However, there is a need to maintain their wetness, and except for conductive polymers it is difficult to sustain dc-induced displacements. For ionic EAP that are involved with water content, the use of voltages above 1.23 V leads to hydrolysis that damages the material irreversibly. Generally, the produced displacement in both the electronic and ionic EAP can be designed geometrically to bend, stretch, or contract. Any of the existing EAP materials can be made to bend with a significant curving response, offering actuators with an easy-to-see reaction and an appealing response. However, bending actuators have relatively limited applications for mechanically demanding tasks due to the low force or torque that can be induced. The various EAP materials have advantages and disadvantages (see Table 1) that determine both their applicability and practical use.

3.2 EAP characterization

Accurate and detailed information about the properties of EAP materials is critical to potential designers who are considering the construction of related mechanisms or devices. In order to assess the competitive capability of EAPs, there is a need for a performance matrix that consists of comparative performance data. Such a matrix needs to show the properties of EAP materials as compared to other classes of actuators, including piezoelectric ceramic, shape memory alloys, hydraulic actuators, and conventional motors. Studies are currently underway to define a unified matrix and establish effective test capabilities with emphasis on the macroscale structures [Bar-Cohen, 2001 and 2004]. Key parameters are identified and test methods are being developed to allow measurements with minimum effect on the EAP material. While the electromechanical properties of longitudinal electronic-type EAP materials can be addressed with some of the conventional test methods, ionic-type EAPs, such as IPMC, are posing technical challenges. The response of these materials suffers complexities that are associated with the mobility of the cation on the microscopic level, the strong dependence on the moisture content, and hysteretic behavior. The use of a video camera and image processing software offers a capability to study the deformation of IPMC strips under various mechanical loads. Simultaneously, the electrical properties and the response to electrical activation can be measured. Nonlinear behavior has been clearly identified in both the mechanical and electrical properties and efforts are underway to model this behavior [Bar-Cohen, 2001and 2004].

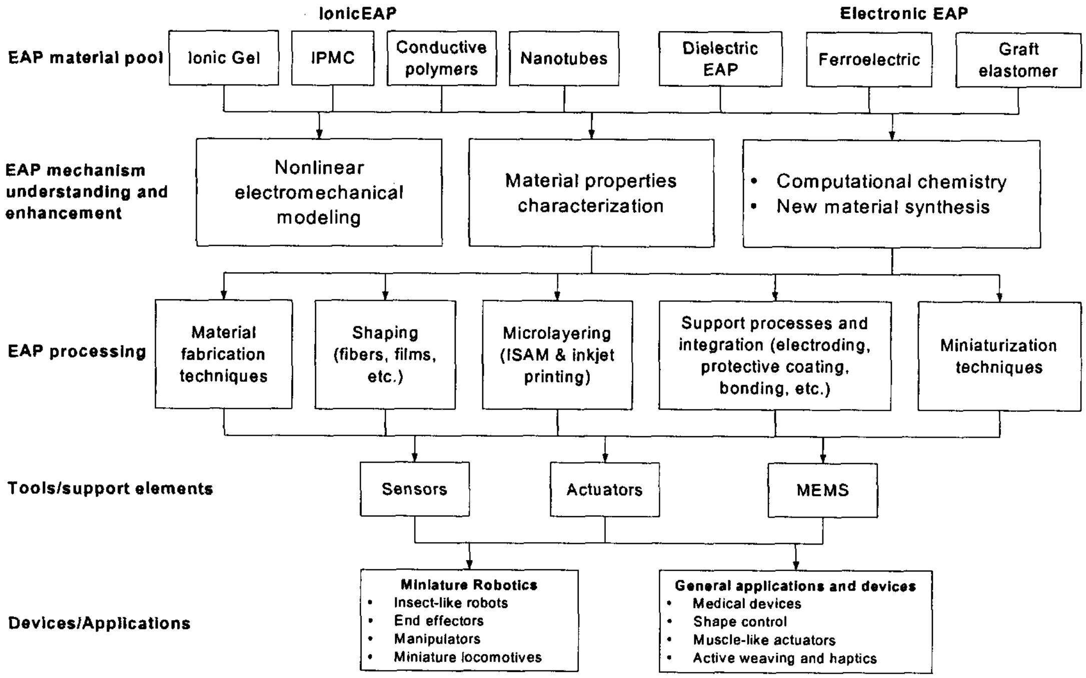


FIGURE 5: EAP infrastructure and areas needing attention.

TABLE 1: Summary of the advantages and disadvantages of the two major EAP groups.

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) • 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 • Due to associated electrostriction effect, a monopolar actuation is produced independent of the voltage polarity.
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 • In aqueous systems, EAP suffer electrolysis at >1.23 V • To operate in air requires attention to the electrolyte. • Low electromechanical coupling efficiency.

3.3 Expected applications

In recent years, there has been significant progress toward making practical EAP actuators, and commercial products are starting to emerge including the fish-robot that was reported earlier. A growing number of organizations are now exploring potential applications for EAP materials and cooperation across many disciplines are helping to overcome some of the challenges. Some of the mechanisms and devices that are being considered are related to aerospace, automotive, medical, robotics, entertainment, toys, clothing, haptic and tactile interfaces, noise control, transducers, power generators and smart structures.

The potential capability of EAPs to emulate muscles may enable robotic capabilities that are in the realm of science fiction when relying on existing actuation materials [Bar-Cohen, 2001& 2004; Bar-Cohen and Breazeal, 2003; Kornbluh et al., 1995]. The large displacement that can be obtained using low mass, low power, and, in some of the EAPs, low voltage, makes them attractive for attempting to produce biologically inspired robots. EAP materials are being sought as a substitute for conventional actuators, possibly eliminating the need for motors, gears, bearings, screws, etc. [Bar-Cohen et al., 1999b; Fischer et al., 1999a]. Combining the bending and longitudinal strain capabilities of EAP actuators, a miniature robotic arm was designed and constructed at JPL. The gripper consists of four IPMC finger strips with hooks at the bottom emulating fingernails. Experiments with this robotic arm raised concerns regarding the ability to control the kinematics of robotic components that are made of dielectric EAP and of IPMC since these actuators are flexible and do not provide accurate positioning. Upon activation, the arm exhibits low-frequency vibration with a relatively low damping. The inherent vibration-damping characteristics of polymers are not sufficient to suppress this low frequency vibration. Besides effective control algorithms, sensor feedback is expected to be critical to addressing the issue of precision positioning of EAP activated devices.

The growing availability of EAP materials that exhibit high actuation displacements and forces is opening new avenues to bioengineering in terms of medical devices and assistance to humans in overcoming different forms of disability. Areas that are being considered include an angioplasty steering mechanism, and rehabilitation robotics. For the latter, exoskeleton structures are being considered in support of rehabilitation or to augment the mobility and functionalities of patients with weak muscles. One important question, which has been asked by new users or researchers/engineers who are comers to this field, is: "where can I 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 to provide "recipes" describing how to make the various EAPs. The address of this website is: http://ndeaa.jpl.nasa.gov/nasa-nde/lommas/eap/EAP-recipe.htm. To help further, 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.

4. PLATFORMS FOR DEMONSTRATION OF EAP

Developing biomimetic intelligent robots involves many disciplines including materials, actuators, sensors, structures, functionality, control, intelligence and autonomous operations [Bar-Cohen and Breazeal, 2003]. Mimicking nature has immensely expanded the collection and functionality of robots. As technology evolves, great numbers of biologically inspired robots that emulate biological creatures are expected to emerge and find applications in our daily life. Even a simple task of staying stable while being pushed is complex for a robot to perform and will require significant progress in many technology areas.

Beside the armwrestling challenge, to promote the development of human-like robots that are actuated by artificial muscles, two platforms were developed and made available to the author at his lab at JPL to support of the worldwide development of EAP. These platforms include an Android head that can make facial expressions and a robotic hand (Figure 6). The head can move the eyes and the lips, whereas the hand allows moving the index finger. At present, conventional electric motors are used to produce the required movement and thus leading to the desired facial expressions of the Android. Once effective EAP materials are developed, they will be modeled into the control system in terms of surface shape modifications and control instructions for the creation of controlled expressions. The robotic hand is equipped with wire-based tendons and has sensors for the operation of the various joints mimicking human hand. This robotic hand is also driven by conventional motors allowing the up and down movement of the index finger of this hand. As the android head, this hand is also used as a baseline for milestone comparison with the performance of emerging EAP actuators. Artificial muscles will substitute the motors when such EAP materials are developed to serve as effective actuators.

FIGURE 6: An android head and a robotic hand that are serving as biomimetic platforms for the development of artificial muscles

ACKNOWLEDGEMENT: This photo was made at JPL where the head was sculptured and instrumented by D. Hanson, University of Texas, Dallas. The hand was made by G. Whiteley, Sheffield Hallam U., UK.

5. FUTURE EXPECTATIONS

Using EAP to replace existing actuators may be a difficult challenge and therefore it is highly desirable to identify a niche application where EAP materials would not need to compete with existing technologies. The large strain response of EAP to electrical stimulation is nonlinear and requires adequate analytical tools for the design and control of related devices. Efforts are currently being made to model this nonlinear electromechanical behavior and to develop experimental techniques of material properties measurements and characterization. These efforts are leading to better understanding of the origin of the electroactivity in various EAP materials, allowing improvement of their performance, and offering effective design tools for simulation of the performance of related devices. Methods of producing EAP fibers and films are being studied to effectively operate EAP materials as actuators and sensors and to improve their robustness.

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 rapid advancements in this field. At the rate of development that is being reported in recent international EAP conferences, it is believed that the authors' armwrestling challenge will be met in few years rather than in many decades from now. Progress toward this goal will lead to great benefits, particularly in the medical area, where EAP materials may be used to replace damaged human muscles, actuate prosthetics and potentially lead to "bionic humans." A remarkable contribution of the EAP field would be to one day seeing a disabled person jogging to the grocery store using this technology.

ACKNOWLEDGMENT

The research at Jet Propulsion Laboratory (JPL), California Institute of Technology, was carried out under a contract with the National Aeronautics and Space Administration (NASA).

REFERENCES

Bar-Cohen Y. (Ed.), "Biomimetics - Biologically-Inspired Technologies," CRC Press, in preparation (expected to be published in Dec. 2004a).

Bar-Cohen Y. (Ed.), "Electroactive Polymer (EAP) Actuators as Artificial Muscles - Reality, Potential and Challenges," ISBN 0-8194-4054-X, SPIE Press, Vol. PM98, (March 2001), pp. 1-671.

Bar-Cohen Y. (Ed.), ibid, 2nd Edition (to be published, March 2004)

Bar-Cohen Y., and C. Breazeal (Eds), "Biologically-Inspired Intelligent Robots," SPIE Press, Vol. PM122, ISBN 0-8194-4872-9 (May 2003), pp. 1-393.

Bar-Cohen Y., S. Leary, K. Oguro, S. Tadokoro, J. Harrison, J. Smith and J. Su, "Challenges to the transition of IPMC artificial muscle actuators to practical application," Proceedings of the 1999 Fall MRS Symposium, Vol. 600, (1999b).

Bar-Cohen Y., T. Xue and S.-S., Lih, "Polymer piezoelectric transducers for ultrasonic NDE," First International Internet Workshop on Ultrasonic NDE, , UTonline Journal, Germany, http://www.ndt.net/article/yosi/yosi.htm (Sept. 1996).

Bar-Cohen, Y., (Ed.), *Proceedings of the Electroactive Polymer Actuators and Devices*, Smart Structures and Materials 1999, SPIE Proc. Vol. 3669, (1999), pp. 1-414.

Chou C.P., B. Hannaford, "Measurement and modeling of McKibben pneumatic artificial muscles," *IEEE Transactions on Robotics and Automation*, Vol. 12, (Feb. 1996), pp. 90-102.

Fischer G., A.G. Cox, M. Gogola, M.K. Gordon, N. Lobontiu, D. Monopoli, E. Garcia, and M. Goldfarb, "Elastodynamic locomotion in mesoscale robotic insects," *Proceedings of the Electroactive Polymer Actuators and Devices*, Smart Structures and Materials 1999, SPIE Proc. Vol. 3669, (1999), pp. 362-368.

Katchalsky, A., "Rapid swelling and deswelling of reversible gels of polymeric acids by ionization," *Experientia*, Vol. V, (1949), pp. 319-320.

Kuhn W., B. Hargitay, A. Katchalsky, and H. Eisenburg, "Reversible dilatation and contraction by changing the state of ionization of high-polymer acid networks," *Nature*, Vol. 165 (1950), pp. 514-516.

Li F. K., W. Zhu, X. Zhang, C. T. Zhao, and M. Xu, "Shape memory effect of ethylene-vinyl acetate copolymers," *J. Appl. Polym. Sci.*, Vol. 71, No. 7 (1999), pp. 1063-1070.

Otero T. F., H. Grande, J. Rodriguez, "A new model for electrochemical oxidation of polypyrrole under conformational relaxation control," *J. Electroanal. Chem.*, Vol. 394 (1995), pp. 211-216.

Pelrine R., R. Kornbluh, and J. P. Joseph, "Electrostriction of polymer dielectrics with compliant electrodes as a means of actuation," *Sensor Actuat. A*, Vol. 64 (1998), p. 77-85.

Steinberg I. Z., A. Oplatka, and A. Katchalsky, "Mechanochemical engines," *Nature*, Vol. 210, (1966) pp. 568-571.

Tobushi H., S. Hayashi, S. Kojima, "Mechanical properties of shape memory polymer of polyurethane series," *JSME Int. J.*, Ser. I. Vol. 35, No 3 (1992), pp. 296-302.

van der Veen G. and W. Prins, *Phys. Sci.*, Vol. 230 (1971), pp. 70.

Zhang Q. M., V. Bharti, and X. Zhao, "Giant electrostriction and relaxor ferroelectric behavior in electron-irradiated poly(vinylidene fluoride-trifluorethylene) copolymer," *Science*, Vol. 280, pp. 2101-2104 (1998).

Zhang Q.M., T. Furukawa, Y. Bar-Cohen, and J. Scheinbeim, Eds., Proceedings of the Fall MRS Symposium on electroactive polymers (EAP), Vol. 600, Warrendale, PA, (1999) pp. 1-336.

Zrinyi M., L. Barsi, D. Szabo, and H. G. Kilian, "Direct observation of abrupt shape transition in ferrogels induced by nonuniform magnetic field," *J. Chem. Phys.*, Vol. 106, No. 13 (1997), pp. 5685-5692.