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Electroactive Polymers as Artificial Muscles: A Review

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Electroactive polymers (EAP) are an emerging class of functional materials that respond to electrical stimulation with large displacement. This attractive characteristic earned them the name artificial muscles. Even though the actuation force and robustness of existing EAP materials require further improvement, there has already been a series of reported successes. The successful applications that were demonstrated include catheter steering element, miniature manipulator, dust wiper, miniature robotic arm, and grippers. Some of the currently considered applications may be difficult to accomplish, and it is important to examine the requirements to the level that current materials can address. Using EAP to replace existing actuators may be a difficult challenge, and therefore it is highly desirable to identify a niche application where it would not need to compete with existing capabilities. The field involves multidisciplines that include materials, chemistry, electromechanics, computers, electronics, etc. A review of the state of the art and some of the challenges to the application of these materials are provided.

Introduction

DURING the past 10 years, new polymers have emerged that respond to electrical stimulation with a significant shape or size change, and this progress has added an important capability to these materials. This capability of the new electroactive polymers (EAP) attracted the attention of engineers and scientists from many different disciplines. Because these materials behave similar to biological muscles, they have acquired the name artificial muscles.[1] Practitioners in biomimetics, a field where robotic mechanisms are developed based on biologically inspired models, are particularly excited about these materials because they can be applied to mimic the movements of animals and insects. In the foreseeable future, robotic mechanisms actuated by EAPs will enable engineers to create devices previously imaginable only in science fiction.

For several decades, it has been known that certain types of polymers can change shape in response to electrical stimulation. Initially, these EAP materials were capable of inducing only a relatively small strain. However, since the beginning of the 1990s, a series of new EAP materials has been developed that can induce large strains leading to a great change in the view of the capability and potential of these materials. Generally, EAPs can induce strains that are as high as two orders of magnitude greater than the striction-limited, rigid and fragile electroactive ceramics. Further, EAP materials are superior to shape memory alloys in higher response speed, lower density, and greater resilience. The current limitations of EAP materials that include low actuation force, mechanical energy density, and robustness are limiting the scope of their practical application.

In recognition of the need for international cooperation among the developers, users, and potential sponsors, the author organized the first EAP conference on 1–2 March 1999 though the Society of Photo-Optical Instrumentation Engineers (SPIE) International as part of the Smart Structures and Materials Symposium.[2] This conference was held in Newport Beach, California, and was the largest ever on this subject, marking an important milestone and turning the spotlight onto these emerging materials and their potential. Following this success, a Materials Research Society conference was initiated to address fundamental issues related to the material science of EAP.[3] The SPIE conferences are now organized annually and have been steadily growing in number of presentations and attendees. Currently, there is a website that archives related information and links to homepages of EAP research and development facilities worldwide, and a semiannual newsletter is issued electronically.

The increased resources, the growing number of investigators conducting research related to EAP, and the improved collaboration among developers, users, and sponsors are expected to lead to rapid progress in the coming years. In 1999, the author posted a challenge to the worldwide community of EAP experts to develop a robotic arm that is actuated by artificial muscles to win an arm wrestling match with a human opponent (Fig. 1). Progress towards this goal will lead to great benefits, particularly in the medical area, including effective prosthetics. Decades from now, EAP may be used to replace damaged human muscles, potentially leading to a "bionic human." A remarkable contribution of the EAP field would be to one day see a disabled person jogging to the grocery store using this technology.

Historical Review and Currently Available Active Polymers

The beginning of the field of EAP can be traced back to an 1880 experiment that was conducted by Roentgen using a rubber band that was charged and discharged with fixed end and a mass attached to the free end.[4] Sacerdote[5] followed this experiment with a formulation of the strain response to electric field activation. Further milestone progress was recorded only in 1925 with the discovery of a piezoelectric polymer called electret, when carnauba wax, rosin, and beeswax were solidified by cooling while subjected to a dc bias field.[6] Generally, electrical excitation is only one of the stimulator types that can induce elastic deformation in polymers. Other simulator types include chemical,[7,8] thermal,[9] pneumatic,[10] optical,[11] and magnetic[12] activation mechanisms.

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.[13] Even though relatively little has since been done to exploit such chemomechanical actuators, this early work pioneered the development of synthetic polymers that mimic biological muscles.[14] 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 poly(vinylidene fluoride) (PVF2) (Refs. 15 and 16), 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 past 10 years, when effective materials that can induce strains that exceed 100% have emerged.[17]

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Table 1 Summary of advantages and disadvantages of two basic EAP groups

Advantages	Disadvantages
Electronic EAP	
Can operate in open air conditions for a long time	Requires compromise between strain and stress
Rapid response (millisecond levels)	Requires high voltages ($\sim$150 MV/m)
Can hold strain under dc activation	Glass transition temperature is inadequate for low-temperature actuation tasks
Induces relatively large actuation forces	
Ionic EAP	
Requires low voltage	Except for CP, ionic EAPs do not hold strain under dc voltage
Provides mostly bending actuation (longitudinal mechanisms can be constructed)	Slow response (fraction of a second)
Exhibit large bending displacements	Bending EAPs induce a relatively low actuation force
	Except for CP and CNT, it is difficult to produce a consistent material (particularly IPMC)
	In aqueous systems the material sustains hydrolysis at $>$1.23 V

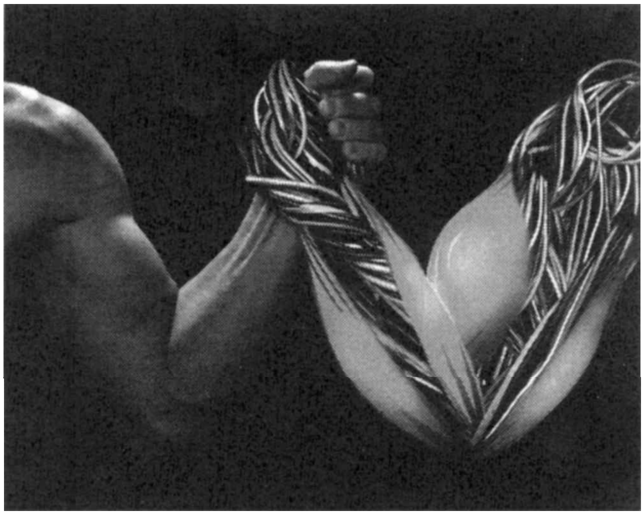


Fig. 1 Grand challenge for the development of EAP actuated robotics.

Generally, EAP can be divided into two major categories based on their activation mechanism: ionic and electronic (Table 1). The electronic polymers (electrostrictive, electrostatic, piezoelectric, and ferroelectric) 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 greater mechanical energy density, and they can be operated in air with no major constraints. However, they require a high activation fields ($>$100 V/μm) close to the breakdown level. In contrast, ionic EAP materials (gels, polymer–metal composites, conductive polymers, and carbon nanotubes) require drive voltages as low as 1–2 V. However, there is a need to maintain their wetness, and except for conductive polymers, it is difficult to sustain dc-induced displacements. The induced displacement of both the electronic and ionic EAP can be geometrically designed 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 due to the low force or torque that can be induced.

Nonelectrical Mechanically Activated Polymers

There are many polymers that exhibit volume or shape change in response to perturbation of the balance between repulsive intermolecular forces that 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, thus, be controlled by subtle changes in parameters such as solvent or gel composition, temperature, pH, light, etc. The type of polymers that can be activated by nonelectrical means include chemically activated[13,18] shape memory polymers,[19,20] inflatable structures, including McKibben muscle (see Ref. 10), light activated polymers,[21–23] magnetically activated polymers,[24] and thermally activated gels.[25–28]

EAP

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).

Electronic EAP

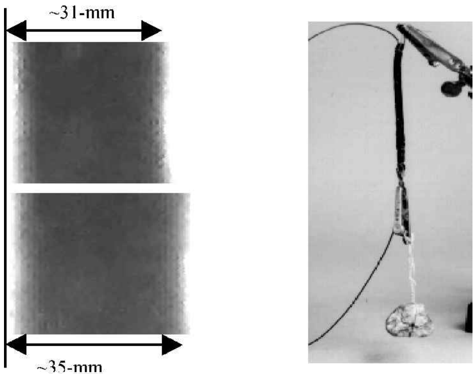
Ferroelectric Polymers

Piezoelectricity was discovered in 1880 by Pierre and Paul-Jacques Curie, who found that, when certain types of crystals are compressed, for example quartz, tourmaline, and Rochelle salt, along certain axes, a voltage is produced on the surface of the crystal. The year afterward, they observed the reverse effect that upon the application of an electric current these crystals sustain an elongation. Piezoelectricity is found only in noncentrosymmetric materials, and the phenomenon is called ferroelectricity when a nonconducting crystal or dielectric material exhibits spontaneous electric polarization. Poly(vinylidene fluoride) (PVDF or PVF2) and its copolymers are the most widely exploited ferroelectric polymers.[15] These polymers are partly crystalline, with an inactive amorphous phase and a Young's modulus near 1–10 GPa. This relatively high elastic modulus offers high mechanical energy density. A large applied ac field ($\sim$200 MV/m) can induce electrostrictive (nonlinear) strains of nearly 2%. Unfortunately, this level of field is dangerously close to dielectric breakdown, and the dielectric hysteresis (loss, heating) is very large. Sen et al.[29] investigated the effect of heavy plasticization ($\sim$65 wt%) of ferroelectric polymers hoping to achieve large strains at reasonable applied fields. However, the plasticizer is also amorphous and inactive, resulting in decreased Young's modulus, permittivity, and electrostrictive strains. Zhang et al.[16] introduced defects into the crystalline structure using electron radiation to dramatically reduce the dielectric loss in P(VDF)–trifluoro–ethylene (TrFE) copolymer. This effect permits ac switching with much less generated heat. Extensive structural investigations indicate that high electron irradiation breaks up the coherence polarization domains and transforms the polymer into a nanomaterial consisting of local nanopolar regions in a nonpolar matrix. It is the electric-field-induced change between nonpolar and polar regions that is responsible for a large electrostriction observed in this polymer. Electrostrictive strains, as large as 5%, can be achieved at low-frequency drive fields having amplitudes of about 150 V/μm. Furthermore, the polymer has a high elastic modulus ($\sim$1 GPa), and the field-induced strain can operate at frequencies higher than 100 kHz, resulting in a very high elastic power density compared with current electroactive polymers. Ferroelectric EAP polymer actuators can be operated in air, vacuum, or water and in a wide temperature range.

Dielectric EAP

Polymers with low elastic stiffness and high dielectric constant can be used to induce large actuation strain by subjecting them to an electrostatic field. This dielectric EAP, also known as electrostatically stricted polymer actuators, can be represented by a parallel plate capacitor.[18] Figure 2a shows a silicone film in a reference (top) and an activated condition. Figure 2b shows an EAP actuator that was made using a silicone film that was scrolled to a shape of rope. The rope, which is about 2 mm in diameter and 3 cm long, was demonstrated to lift and drop about 17-g rock using about 2.5 kV.

The induced strain is proportional to the electric field square times the dielectric constant and inversely proportional to the elastic



a) b)

Fig. 2 Under electroactivation, a dielectric elastomer with electrodes on both surfaces expands laterally and can be made to operate longitudinally.

a) b) c)

Fig. 3 Electrostrictive grafted elastomer-based bimorph actuator in a) one direction excited state, b) unexcited state, and c) opposite direction excited state (courtesy of J. Su, NASA Langley Research Center).

modulus. This use of polymers with high dielectric constants and application of high electric fields leads to large forces and strains. To reach the required electric field levels, one needs to either use high voltage and/or employ thin films. Under an electric field, the film is squeezed in the thickness direction, causing expansion in the transverse direction. For a pair of electrodes with circular shape, the diameter and thickness changes can be determined using the volume conservation of the film. This characteristic allows producing longitudinal actuators using dielectric elastomer films with flexible electrodes that appear to act similarly to biological muscles. Dielectric EAP actuators require large electric fields (~100 V/μm) and can induce significant levels of strain (10–200%). Overall, the associated voltages are close to the breakdown strength of the material, and a safety factor that lowers the potential needs to be used. Moreover, the relatively small breakdown strength of air (2–3 V/μm) presents an additional challenge. Recently, Stanford Research Institute International researchers identified a new class of polymers that exhibits an extremely high strain response.[30] These acrylic elastomers (such as 3M™ VHB™ tapes) have produced planar strains of more than 300% for biaxially symmetric constraints and linear strains of up to 215% for uniaxial constraints.

Electrostrictive Graft Elastomers

In 1998, a graft-elastomer EAP, which exhibits a large electric-field-induced strain due to electrostriction,[31] was developed at NASA Langley Research Center. This electrostrictive polymer consists of two components, a flexible backbone macromolecule and a grafted polymer that can form crystalline. The grafted crystalline polar phase provides moieties to respond to an applied electric field and cross-linking sites for the elastomer system. This material offers high electric-field-induced strain (~4%), high electromechanical power, and excellent processability. Combination of the electrostrictive-grafted elastomer with a piezoelectric P(VDF–TrFE) copolymer yields several compositions of a ferroelectric-electrostrictive molecular composite system. This combination can be operated both as a piezoelectric sensor and as an electrostrictive actuator. Careful selection of the composition allows creating and optimizing the molecular composite system with respect to the electrical, mechanical, and electromechanical properties. An example of an electroactivated graft EAP is shown in Fig. 3 for a bimorph actuator fabricated using a backing with a passive grafted elastomer. The actuator can bend in both directions under controlled electric field excitation.

Electrostrictive Paper

The use of paper as an electrostrictive EAP actuator was demonstrated at Inha University, Republic of Korea.[32] Paper is composed of a multitude of discrete particles, mainly of a fibrous nature, which forms a network structure. Because paper is produced in various mechanical processes with chemical additives, it is possible to prepare a paper that has electroactive properties. Such an EAP actuator was prepared by bonding two silver laminated papers with the silver electrodes placed on the outside surface. When an electric voltage was applied to the electrodes, the actuator produces bending displacement, and its performance depends on the excitation voltages, frequencies, type of adhesive, and the host paper. Studies indicate that the electrostriction effect that is associated with this actuator is the result of electrostatic forces and an intermolecular interaction of the adhesive. The demonstrated actuator is lightweight and simple to fabricate. Various applications are currently being considered including active sound absorbing materials, flexible speakers, and smart shape control devices.

Electroviscoelastic Elastomers

Electroviscoelastic elastomers represent a family of electroactive polymers that are composites of silicone elastomer and a polar phase. Before cross linking, in the uncured state, they behave as electrorheological fluids. An electric field is applied during curing to orient and fix the position of the polar phase in the elastomeric matrix. These materials then remain in the solid state but have a shear modulus (both real and imaginary parts) that changes with applied electric field, <6 V/μm (Ref. 33). A stronger magnetorheological effect can also be introduced in an analogous manner, and as much as a 50% change in the shear modulus can be induced.[24,34] These materials may be used as alternatives to electrorheological fluids for active damping applications.

Liquid Crystal Elastomer Materials

Liquid crystal elastomers (LCE) were pioneered at Alber-Ludwigs Universitat, Freiburg, Germany.[35] These materials can be used to form an EAP actuator that has piezoelectric characteristics as well as electrically activatable by inducing joule heating. LCE are composite materials that consist of monodomain nematic liquid crystal elastomers and conductive polymers that are distributed within their network structure.[36] The actuation mechanism of these materials involves phase transition between nematic and isotropic phases over a period of less than 1 s. The reverse process is slower, taking about 10 s, and it requires cooling to cause expansion of the elastomer to its original length. The mechanical properties of LCE materials can be controlled and optimized by effective selection of the liquid crystalline phase, density of cross linking, flexibility of the polymer backbone, coupling between the backbone and liquid crystal group, and the coupling between the liquid crystal group and the external stimuli,[37] where a rapid contraction appears when the phase transition occurs and the thermomechanical behavior is hysteretic.

Ionic EAP

Ionic Polymer Gels

Polymer gels can be synthesized to produce strong actuators having the potential of matching the force and energy density of biological muscles. These materials, for example, polyacrylonitrile, are generally activated by a chemical reactions; changing from an acid to an alkaline environment causes the gel to become dense or swollen, respectively. This reaction can be stimulated electrically as was shown by researchers at the University of Arizona.[38] When activated, these gels bend as the cathode side becomes more alkalinic and the anode side more acidic. However, the response of this multilayered gel structure is relatively slow because of the need to diffuse ions through the gel. A significant amount of research and development, as well as applications using ionic polymer gels (IPG) were explored at Hokkaido University, Japan. The polymers that

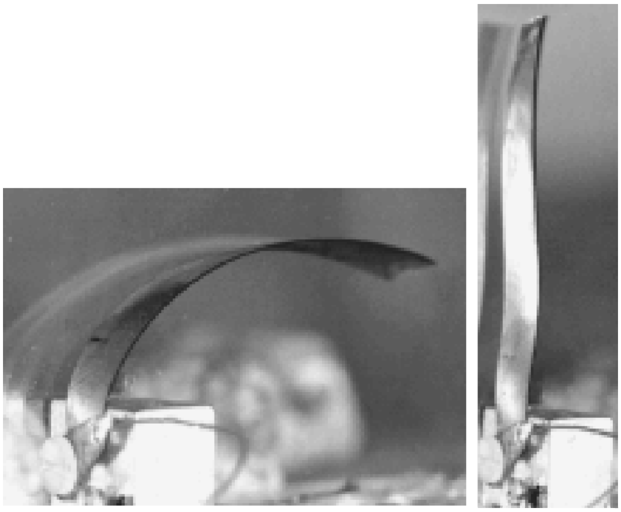


Fig. 4 IPMC in activated and reference states.

were explored include electrically induced bending of gels[28] and electrical-induced reversible volume change of gel particles.[39] Recently, Schreyer et al.[19] used a combination of ionic gel and conductive polymer electrodes to demonstrate an effective EAP actuator.

Ionomeric Polymer–Metal Composites

Ionomeric polymer–metal composite (IPMC) is an EAP that bends in response to an electrical activation (Fig. 4) as a result of mobility of cations in the polymer network. In 1992, IPMC was realized to have this electroactive characteristic by three groups of researchers, one in Japan[40] and two in the United States.[41,42] The operation as actuators is the reverse process of the charge storage mechanism associated with fuel cells. A relatively low voltage is required to stimulate bending in IPMC, where the base polymer provides channels for mobility of positive ions in a fixed network of negative ions on interconnected clusters. Two types of base polymers are used to form IPMC: Nafion® (perfluorosulfonate made by DuPont) and Flemion® (perfluorocaboxylate, made by Asahi Glass, Japan). Before these base polymers, were used as EAP, they were widely employed in fuel cells for production of hydrogen (hydrolysis).[43] To electrode chemically, the polymer films, metal ions (platinum, gold, or others) are dispersed throughout the hydrophilic regions of the polymer surface and are subsequently reduced to the corresponding zero-valence metal atoms. Generally, the ionic content of the IPMC is an important factor in the electromechanical response of these materials.[44,45] Examining the bending response shows that using low voltage (1–10 V) induces a large bending at frequencies below 1 Hz, and the displacement significantly decreases with the increase in frequency. In recent years, the bending response of IPMC was enhanced using Li$^+$ cations that are small and have higher mobility or large tetra–n–butylammonium cations that transports water in a process that is still under study. The actuation displacement of IPMC was further enhanced using gold metallization as a result of the higher electrode conductivity.

Conductive Polymers

Conductive polymers (CP) typically function via the reversible counterion insertion and expulsion that occurs during redox cycling.[8] Oxidation and reduction occur at the electrodes inducing a considerable volume change mainly due to the exchange of ions with an electrolyte. A sandwich of two conductive polymer electrodes, for example, polypyrrole or polyaniline, or PAN doped in HCl, with an electrolyte between them forms an EAP actuator. When a voltage is applied between the electrodes, oxidation occurs at the anode and reduction at the cathode. Ions (H$^+$) migrate between the electrolyte and the electrodes to balance the electric charge. Addition of the ions causes swelling of the polymer, and conversely their removal results in shrinkage and as a result the sandwich bends. One of the parameters that affect the response is the thickness of the layers: Thinner layers are faster (as fast as 40 Hz) but induced lower force. Because strong shear forces act on the electrolyte layer, attention is needed to protect the material from premature failure. Conductive polymer actuators generally require voltages in the range of 1–5 V, and the speed increases with the voltage having relatively high mechanical energy densities of over 20 J/cm^3 but with low efficiencies at the level of 1% (Ref. 46).

Various approaches are being considered to operate this EAP in dry environments, where the use of quasi-solid electrolytes and the application of protective coating are some of the alternatives. In recent years, several conductive polymers were reported including PPy, polyethylenedioxythiophene, poly(p–phenylene vinylene)s, polyaniline, and polythiophenes. Complexes between PPy and sulfonated detergents offer relatively good stability in aqueous media, but are relatively soft compared to other conjugated polymers. Most actuators that use conductive polymers exploit voltage controlled swelling to induce bending. Conjugated polymer microactuators were first fabricated at the Link Pings Universitet, Sweden. Among the devices that were demonstrated were miniature boxes that can be opened and closed.[47] With use of this technology, a micro robot was developed, and other applications may evolve including surgical tools or robots to assemble other microdevices in a factory on a desk.[48]

Operation of CP as actuators at the single-molecule level is currently being studied, taking advantage of intrinsic electroactive property of individual polymer chains. Researchers[49] at the University of California, Riverside, used {4n}annulene chemistry as a method of encoding actuation into individual polymer chains. It is well known that cyclooctatetraene (a tube-shaped {8}annulene) becomes planar on oxidation or reduction. During such a process, the distance between carbons 1 and 4 is altered. When an {8} annulene is utilized as a polymer repeat unit, such redox-induced conformational changes can be translated into a change in the effective monomer length. The effective polymer chain length is ultimately altered, causing the alteration of the effective length of the monomer. Thus, a single-molecule electromechanical actuator can be enabled.

Carbon Nanotubes

In 1999, carbon nanotubes (CNT) with diamondlike mechanical properties emerged as formal EAP.[50] The carbon–carbon bond in nanotubes (NT) that are suspended in an electrolyte and the change in bond length are responsible for the actuation mechanism. A network of conjugated bonds connects all carbons and provides a path for the flow of electrons along the bonds. The electrolyte forms an electric double layer with the NT and allows injection of large charges that affect the ionic charge balance between the NT and the electrolyte. The more charges injected into the bond, the larger is the dimension change. Removal of electrons causes the NT to carry a net positive charge, which is spread across all of the carbon nuclei causing repulsion between adjacent carbon nuclei and increasing the C–C bond length. Injection of electrons into the bond also causes lengthening of the bond resulting increase in NT diameter and length. These dimension changes are translated into macroscopic movement in the network element of entangled NT, and the net result is extension of the CNT.

When the mechanical strength and modulus of the individual CNTs and the achievable actuator displacements are considered, this actuator has the potential of providing work per cycle that is higher than any previously reported actuator technologies and of generating much higher mechanical stresses. The material consists of nanometer size tubes, and it was shown to induce strains at the range of 1% along the length. The key obstacle to the commercialization of this EAP is it high cost and the difficulty in mass production of the material.

Electrorheological Fluids

Electrorheological fluids (ERFs) experience dramatic changes in their viscosity, when subjected to an electric field. These fluids are made from suspensions of an insulating base fluid and particles 0.1–100 μm in size. Winslow first explained the electrorheological effect in the 1940s using oil dispersions of fine powders.[51] The electrorheological effect, sometimes called the Winslow effect, is thought to arise from the difference in the dielectric constants of the fluid and particles. In the presence of an electric field, the particles, due to

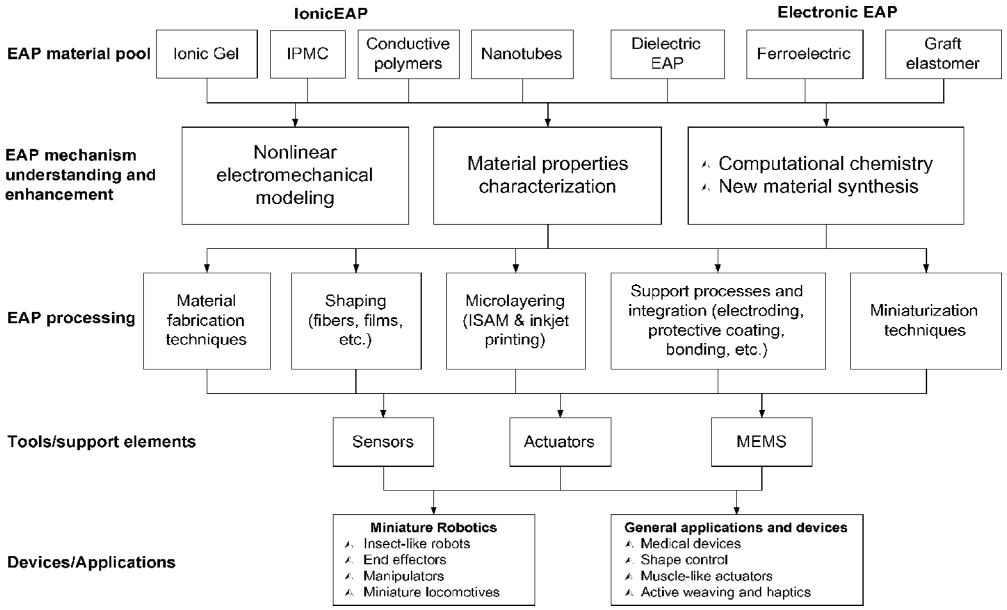


Fig. 5 EAP infrastructure and areas needing attention.

an induced dipole moment, will form chains along the field lines. This induced structure changes the ERF's viscosity, yield stress, and other properties, allowing the ERF to change consistency from that of a liquid to something that is viscoelastic, such as a gel, with response times to changes in electric fields on the order of milliseconds. A good review of the ERF phenomenon and the theoretical basis for their behavior can be found in Ref. 52. Control over a fluid's rheological properties offers the promise of new possibilities in engineering for actuation and control of mechanical motion. The ability to control the viscosity and the rapid response of ERF allow simplification of the mechanisms that are involved with hydraulics. Their solidlike properties in the presence of a field can be used to transmit forces over a large range and a large number of applications have been found including shock absorbers, active dampers, clutches, adaptive gripping devices, and variable flow pumps.

Need for 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 microelectromechanical systems MEMS sensors to produce smart actuators. As mentioned earlier, their most attractive feature is their ability to emulate the operation of biological muscles with high fracture toughness, large actuation strain, and inherent vibration damping.

Unfortunately, the EAP materials that have been developed so far are still exhibiting low force, are far below their efficiency limits, and are not robust. There is no standard commercial material available for consideration in practical applications. The documented EAP materials that induce large strains are driven by many different phenomena.[3,45,53] Each of these materials requires adequate attention to their unique properties and constraints. To be able to take these materials from the development phase to use as effective actuators, there is a need to establish an adequate EAP infrastructure. The author's view of this infrastructure and the areas that need development are shown schematically in Fig. 5. Effectively addressing the requirements of the EAP infrastructure involves developing adequate understanding of EAP materials' behavior, as well as processing and characterization techniques. Enhancement of the actuation force requires understanding the basic principles using computational chemistry models, comprehensive material science, electromechanics analytical tools, and improved material processing techniques. Efforts are needed to gain a better understanding of the parameters that control the EAP electroactivation force and deformation. The processes of synthesizing, fabricating, electroding, shaping, and handling will need to be refined to maximize the EAP materials actuation capability and robustness. Methods of reliably characterizing the response of these materials are required to establish a database with documented material properties to support design engineers considering use of these materials and toward making EAP actuators of choice. Various configurations of EAP actuators and sensors will need to be studied and modeled to produce an arsenal of effective, smart, EAP-driven systems. The development of the infrastructure is a multidisciplinary task, and it requires international collaboration.

Conclusions

Electroactive polymers have emerged with great potential and enabled the development of unique devices that are biologically inspired. The development of an effective infrastructure for this field is critical to the commercial availability of robust EAP actuators and the emergence of practical applications. The challenges are enormous, but the recent trend of international cooperation, the greater visibility of the field, and the surge in funding of related research are offering great hope for the future of these exciting new materials. The potential to operate biologically inspired mechanisms driven by EAP as artificial muscles is offering capabilities that are currently considered science fiction. The author's arm-wrestling challenge for a match between EAP-actuated robots and a human opponent highlights the potential of EAP. Progress toward this goal will lead to great benefits to mankind, particularly in the area of medical prosthetics. The author believes that an emergence of a niche application that addresses a critical need will significantly accelerate the transition of EAP from novelty to actuators of choice. In niche cases, these materials will be used in spite of their current limitations while taking advantage of their uniqueness.

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