APPLICATIONS OF ELECTROACTIVE POLYMER IN ELECTRONICS AND MECHATRONICS

Komal Powar, Prasad Vengurlekar

Abstract - Electroactive polymer emerged in recent years with great potential to enabling unique mechanism. Mechatronics and electronics devices and system based on electroactive polymers are fast-growing area for research and development. Electroactive polymers are capable of changing size and shape with varying electric field. They possess unique properties such as high mechanical flexibility, low density, structural simplicity, no acoustic noise, low cost etc. Electroactive polymers are involved in various field of engineering including robotics, automation, energy harvesting, development of actuators and sensors, aviation technology. This paper represents introduction and overview of electroactive polymers in different areas of application.

Key word: Electroactive polymer, actuator, sensor, aviation, artificial muscle, electronic EAP, ionic EAP

1 Introduction

EAP materials have properties that make them very attractive for a wide variety of applications. As polymers,
EAP materials can be easily formed in various shapes, their properties can be engineered, and they can potentially be integrated with sensors to produce smart actuators

A growing number of organizations are exploring potential applications for EAP materials, and cooperation across many disciplines is helping to overcome the related challenges. The mechanisms and devices that are being considered or developed are applicable to aerospace, automotive, medical, robotics, exoskeletons, articulation mechanisms, entertainment, animation, toys, clothing, haptic and tactile interfaces, noise control, transducers, power generators, and smart structures.

The activation mechanism of such polymers include electric, chemical, pneumatic, optical, and magnetic. Electrical excitation is one of the most attractive stimulators that can produce elastic deformation in polymers. The convenience and the practicality of electrical stimulation and the continual improvement in capabilities make the EAP materialsEAPs show unique properties, such as sizable electrically driven active strains or stresses, high mechanical flexibility, low density, structural simplicity, ease of processing and scalability, no acoustic noise and, in most cases, lowcosts. Owing to their functional and structural properties, electromechanical transducers based on these materials are usually refereed to as EAP artificial muscles

EAP materials are typically classified in two major classes:ionic EAPs and electronic EAPs. The former are activated by an electrically induced transport of ions and/or solvent, while the latter are activated by electrostatic forces. Ionic EAPs comprehend polymer gels, ionic polymer metal composites, conducting polymers, and carbon nanotubes. Electronic EAPs compre-hend piezoelectric polymers, electrostrictive polymers, dielectric elastomers, liquid crystal elastomers, and carbon nanotube aerogels.

2 Classification

2.1 ELECTRIC EAP

2.1.1 Ferroelectric polymer

Ferroelectric materials are analogous to ferromagnets, where the application of an electric field aligns polarized domains in the material. Permanent polarization
exists even after the removal of the field, and the curie temperature in ferroelectric materials, similar to ferromagnetic materials, disrupts the permanent polarization through thermal energy [1]. Poly(vinylidene fluoride-trifluoroethylene) (P(VDF-TrFE)) is commonly used ferroelectric polymer. Local dipoles are created on the polymer backbone due to the

high electronegativity of fluorine atoms. Polarized domains are generated by these local dipoles aligning in an electric field. The alignment is retained even after the removal of electric field, and the reversible, conformational changes produced by this realignment are used for actuation [1].

The polymers have a Young's modulus of nearly 1–10 GPa, which allows high mechanical energy density to be obtained. Up to 2% electrostatic strains were obtained with the application of a large electric field (~200 MV/m) which is nearly equal to the dielectric breakdown field of the material [2]. Up to a 10% strain as observed in ferroelectric polymers during the transition from the ferroelectric phase to the paraelectric phase.

2.1.2 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 electro-stat axially stricted polymer (ESSE') actuators, can be represented by a parallel plate capacitor . Figure 1 shows a silicone film that in a reference (top) and activated conditions. The right section of the figure shows an EAP actuator that was made using a silicone film that was scrolled to a shape of rope. The rope that is about 2-mn diameter and 3-cm long was demonstrated to lift and drop about 17-gram rock using about 2.5-KV.

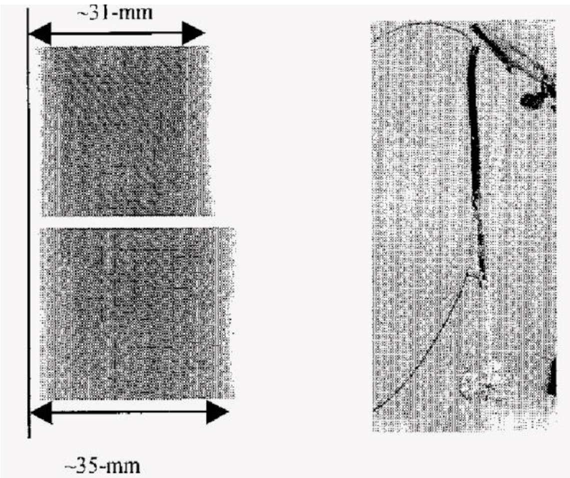

Fig1 : silicon film

The induced strain is proportional to the electric field square, times the dielectric constant in inversely proportional to the elastic modulus. 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. Dielectric EAP actuators require large electric fields (-100 V/prn) 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[3]

2.1.3 Electrostrictive Graft Elastomers

In 1998, a graft-elastomer EAP was developed at NASA Langley Research Center exhibiting a large electric field induced strain due to electrostriction [Su, et al, 1999]. 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 response 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 elastomerwith a piezoelectric poly(vinylidene fluoride-trifluoroethylene) copolymer yields several compositions of a ferroelectric-electrostrictive molecular composite system. Such combination can be operated both as piezoelectric sensor and as an electrostrictive actuator[4].

2.1.4 Electro-Viscoelastic Elastomers

Electro-viscoelastic elastomers represent a family of electroactive polymers that are composites of silicone elastomer and a polar phase. Before crosslinking, in the uncured state, they behave as electro-rheological 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 Vipm) [Shiga, 1997]. A stronger magneto-rheological effect can also be introduced in an analogous manner and as much as a 50% change in the shear modulus can be induced. These materials may be used as alternatives to electrosheological fluids for active damping applications[4].

2.1.5 Liquid Crystal Elastomer (LCE) Materials

Liquid crystal elastomers were pioneered at Alber-Ludwigs Universitat (Freiburg, Germany) . 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 . The actuation mechanism of these materials involves phase transition between nematic and isotropic phases oves a period of less than a second. The reverse process is slower, taking about 10- sec, 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 crosslinking, 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, where a rapid contraction appears when the phase transition occurs and the thermo-mechanical behavior is hysteretic[4].

2.2 IONIC EAP

2.2.1 Ionic Polymer Gels (IPG)

Polymer gels can be synthesized to produce strong actuators having the potential of matching the force and energy density of biological muscles. These materials are generally activated by a chemical reactions, changing from an acid to an alkaline environment causes the gel to become dense or swollen, respectively. 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.

2.2.2 Ionomeric Polymer-Metal Composites (IPMC)

Ionomeric polymer-metal composite (IPMC) is an EAP that bends in response to an electrical activation (Figure2) as **a** result of mobility of cations in the polymer network .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: NafionB (perfluorosulfonate made by DuPont) and FlemionR (perfluorocaboxylate, made by Asahi Glass, Japan. Prior to using these base polymers as EAP, they were widely employed in fuel cells for production of hydrogen Generally, the ionic content of the IPMC is an important factor in the electromechanical response of these materials Examining the bending response shows that using low voltage (1-10 Volts) induces a large bending at frequencies below 1-Hz, and the displacement significantly decreases with the increase in frequency[3]. 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 catioiis that transports water in a process that is still under studies. The actuation displacement of IPMC was further enhanced using gold metallization as a result of the higher electrode conductivity

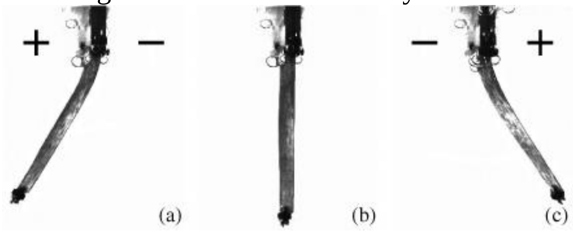

Fig2 : IPMC activation while applying voltage .

2.2.3 Conductive Polymers (CP)

Conductive polymers typically function via the reversible counter-ion insertion and expulsion that occurs during redox cycling .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 (e.g., polypyrrole or polyaniline, or PAN doped in BC1) 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. 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 a€ over 20 J/cm3 but with low efficiencies at the level of 1%[30].

2.2.4 Carbon Nanotubes (CNT)

In 1999, carbon nanotubes with diamond-like mechanical properties emerged as formal EAP. 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 nanotubes and allows injection of large charges that affect the ionic charge balance between the NT and the electrolyte. The more charges are injected into the bond the larger the dimension change. Removal of electrons causes the nanotubes to carry a net positive charge, which is spread across all 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 nanotubes diameter and length. These dimension changes are translated into macroscopic movement in the network element of entangled nanotubes and the net result is extension of the CNT[30].

3 Synthesis

EAPs are very new materials in terms of their properties but their synthesis is very much easier because of their constituent molecules. Most of the EAPs contain organic aromatic or unsaturated molecules and to obtain these molecules is very easy as their synthesis methods are developed over a large period of time to get the best yield and purity combinations. Examples of the EAPs are polyaniline (PANi), polypyrole (PPy), polythiophene, polyvinylidene fluoride (PDVF), etc.

Different EAPs have different methods of synthesis and there is a lot research going on new innovative methods. Here, the synthesis of the most commonly used EAP is discussed. That EAP is Polyaniline (PANi); it is easy obtaining its raw material and it has a very simple synthesis and hence its applications are very versatile in the industry. Conducting PANi is prepared either by electrochemical oxidative polymerisation method or by chemical oxidative polymerisation method. The chemical method has better yield than the electrochemical method. Other synthesis methods proposed are plasma polymerisation, autocatalytic polymerisation and inverse emulsion polymerisation.

Polyaniline have its various conducting properties due to the – NH – group, which is present at the para - positions of the two aromatic phenyl rings. Polyaniline has various oxidation states out of which the 50% oxidised emeraldine salt shows conductivity while other states require doping to develop conductivity. The various oxidation states of the PANi are interconvertable by simple protonation and deprotonation reactions. These oxidation states also show colour changes during conversion. Interconversion of the various oxidation stayes is given in the figure and the colour and conductivity of each state is given in the table.

3.1 Chemical synthesis

Synthesis of PANI by chemical oxidation way involves the use of either hydrochloric or sulfuric acid in the presence of ammonium persulfate as the oxidizing agent in the aqueous medium. The principal function of the oxidant is to withdraw a proton from an aniline molecule, without forming a strong co-ordination bond either with the substrate / intermediate or with the final product. However smaller quantity of oxidant is used to avoid oxidative degradation of the polymer formed. Polymer chains proceeds by a redox process between the growing chain and aniline with addition of monomer to the chain end. The high concentration of a strong oxidant, $(NH_4)_2S_2O_8$, at the initial stage of the polymerization enables the fast oxidation of oligomers and polyaniline, as well as their existence in the oxidized form.

Chemical synthesis requires three reactants: aniline, an acidic medium (aqueous or organic) and an oxidant. The more common acids are essentially hydrochloric acid (HCl) and sulfuric acid (H_2SO_4). Ammonium persulfate ($(NH_4)_2S_2O_8$), potassium dichromate ($K_2Cr_2O_7$), cerium sulfate ($Ce(SO_4)_2$), sodium vanadate ($NaVO_3$), potassium ferricyanide ($K_3(Fe(CN)_6)$), potassium iodate (KIO_3), hydrogen peroxide (H_2O_2) are recommended as oxidants . However, the more popular synthesis is run with a 1 mol aqueous hydrochloric acid solution (pH between 0 and 2), ammonium persulfate as oxidant with an oxidant/aniline molar ratio ≤1.15 in order to obtain high conductivity and yield. The solution temperature is comprised between 0 and 2 ◦C in order to limit secondary reactions. The duration of the reaction varies generally between 1 and 2 hr. The experimental part consists of adding slowly (even drop by drop) the aqueous ammonium persulfate solution to the aniline/HCl solution, both solutions being precooled to nearly 0 ◦C. The mixture is stirred for about 1 hr. The obtained precipitate is removed by filtration and washed repeatedly with HCl and dried under vacuum for 48 [28].The obtained material is polyemeraldine salt: polyemeraldine hydrochloride (PANIHCl), green colored. To obtain polyemeraldine base, polyemeraldine hydrochloride is treated in an aqueous ammonium hydroxide solution for about 15 hr. The obtained powder is washed and dried.

3.2 Electrochemical synthesis

The electrochemical synthesis of conducting polymer is an electro-organic process rather than an organic electrochemical one, because the more emphasis is on the electrochemistry and electrochemical process rather than on organic synthesis. Electrochemistry has contributed significantly to the developments in conducting polymers. In most of the applications, it is essential to synthesize polymers into a thin film of well defined structure, preferably with a large area. For preparation of such films, electrochemical synthesis is a standard method. The conducting polymers which are not easily processed, when prepared by chemical routes, are synthesized in the form of films adhering to the electrode, so that a study of the optical and electrical properties can be carried out in-situ by using electroanalytical techniques. The electrochemical synthesis of conducting polymers is similar to the electrodeposition of metals from an electrolyte bath; the polymer is deposited on the electrode surface and also in the in-situ doped form.

Three electrochemical methods can be used to PANI synthesis

a)Galvanostatic method when applied a constant current,

b) Potentiostatic method with a constant potential,

c) Potentiodynamic method where current and potential varies with time.

Whatever the method is, a three-electrode assembly composes the reactor vessel: a working electrode on which the polymer is deposited, a counter electrode also named auxiliary electrode (platinum grid) and a reference electrode (in most cases, a saturated calomel electrode (SCE)). The more common working electrode is a platinum one, but PANI depositions have also been realized onto conducting glass (glass covered by indium-doped tin oxide (ITO) electrode), Fe, Cu, Au, graphite, stainless steel, etc. PANI can be then peeled off from the electrode surface by immersion in an acidic solution.

As compared to chemical synthesis, this route presents several advantages as cleanness because no extraction from the monomer–solvent–oxidant mixture is necessary, doping and thickness control via electrode potential, simultaneous synthesis and deposition of PANI thin layer.

The electrochemical synthesis route offers many advantages over the chemical method listed below.

- It is simple and less expensive technique. Therefore, electrodeposition of conducting polymer on oxidizable conducting glass is extremely economical.
- Unlike chemical method, there is no need of catalyst and therefore, the

electrodeposited polymers and co-polymers are essentially pure and homogeneous.

- Doping of the polymer with desired ion can be considered simultaneously by changing the nature of ions in the solution.
- The conducting polymers can be obtained directly in thin film forms as coating on electrodes and the properties of these coatings can be controlled effectively by proper choice of the electrochemical process variables.
- Reduction in the possible pollution by adopting the suitable system for electropolymerization using modern sophisticated instrument.

The electrochemical synthesis is normally carried out in a single compartment cell. The cell consists of the electrodes, electrolyte and power supply.

4 Sensors based on ionic polymer–metal composites

Similar to the CPs, IPMCsensors and actuators alsowork based on the movement of ions, but with different mechanisms and structures. IPMCs have trilayer structures, involving a combination of ionic polymers and metallic electrodes. IPMCs are reported as both sensors and actuators [19]. Working as sensors, their great sensitivity to physical stimuli such as mechanical force. Two methods to measure mechanical deformation have been proposed, as described below.
In the first method, the generated potential difference between electrodes is measured. The IPMC’s mechanical sensing properties were explained by the charge imbalance of ion migration by mechanical deformation . When the external force is imposed on the IPMC sensor, due to the stress strain gradient, shifting of mobile cations becomes possible and they move towards the expanded region to balance the concentration of ions. The gradient of charge along the thickness of the IPMC sensor generates a potential difference which can be detected by a low-power amplifier or open circuit potential measurement . The hypothesis behind this mechanism of sensing is that the charge density is proportional to the induced strain . In the second measurement method, the surface resistance of the metallic electrode of IPMC is measured. This resistance changes with expansion and contraction of the electrodes. When the electrode is stretched the resistance increases, and compression of the electrode decreases the resistance. In the case of bending IPMCs under applied force or strain, the resistance of one side increases while the other side decreases. This difference between resistances of both surfaces is correlated to the bending curvature and also increases cumulatively. The measured resistance difference between electrodes is used to calculate the radius of curvature, which leads us to find the applied strain. A four-probe system is employed to measure the surface resistance of the electrodes [19].

IPMCs can be used for both static and dynamic mechanical sensing. They demonstrate potential in sensing curvature variation for engineering structures

As shown in Figures 3 and 4, IPMC strips generally bend towards the anode and if the voltage signal is reversed they also reverse their direction of bending. Conversely by bending the material, shifting of mobile charges become possible due to imposed stresses. Consider Figure 4 where a rectangular strip of the composite sensor is placed between two electrodes. When the composite is bent a stress gradient is built on the outer fibers relative to the neutral axis**.** The mobile ions therefore will shift toward the favored region where opposite charges are available. The deficit in one charge and excess in the other can be translated into a voltage gradient which is easily sensed by a low power amplifier

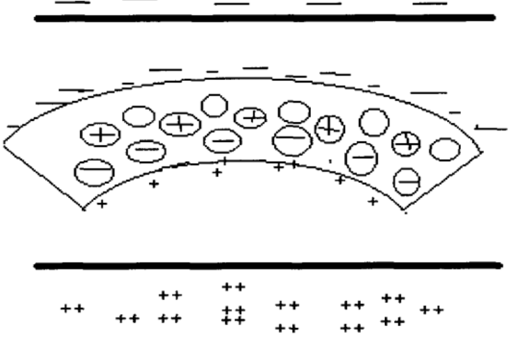

Fig 3. General redistribution of charges in an ionic polymer due to an imposed electric field.

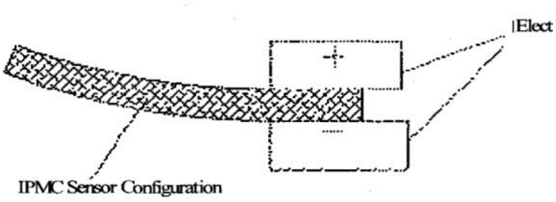

Fig4**.** Simple IPMC sensor placed between two electrode.

4.1 Quasi- Static Sensing

The experimental results showed that a linear relationship exists between the voltage output and imposed quasi-static displacement of the tip of the IPMC sensor . The experimental set up was such that the tip of the cantilevered IPMC strip as shown in Figure 5 was mechanically moved and the corresponding output voltage recorded[17].

4.2 Dynamic Sensing

When strips of IPMC are dynamically disturbed by means of a dynamic impact or shock loading, a damped electrical response is observed. The dynamic response was observed to be highly repeatable with a fairly high band width to 100's of Hz.. This particular property of IPMC's may find a large number of applications in large motion sensing devices for a variety of industrial applications. Since these muscles can also be cut as small as one desires, they present a tremendous potential to micro-electro-mechanical systems (MEMS) sensing and actuation applications[17].

4.3Linear and Platform Type Actuators

polyelectrolytes are for the most part three dimensional network of macromolecules cross-linked nonuniformly, the concentration of ionic charge groups are also nonuniform within the polymer matrix. Therefore the mechanism of bending is partially related to migration of mobile ions within the network due to imposition of an electric field . However, recent investigation point to a stronger effect due to surface charge interactions which will be reported later. Figure 5 depicts the bending deformation of a typical strip with varying electric field, while Figure 4 displays the variation of deformation with varying frequency of alternating electric field .Based on such dynamic deformation characteristics, linear and platform type actuators can be designed and made dynamically operational. These types of actuators are shown in Figure 6 and 7 .

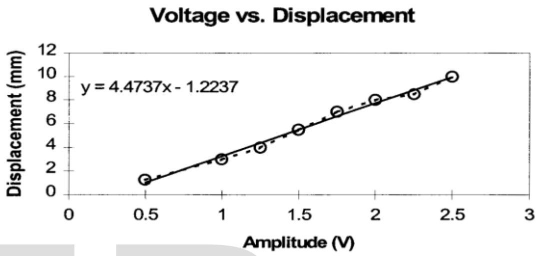

Fig 5-Bending Displacement versus Voltage for a typical IPMC strip of 5mmx0.20mmx20mm under a frequency of 0.5Hz.

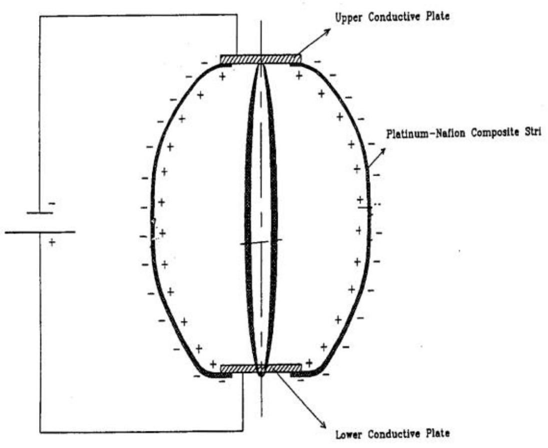

Fig 6**-** A typical linear-type robotic actuators made with IPMC legs

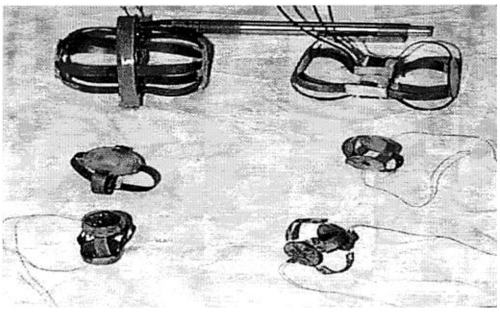

Fig **7-** An assortment of Linear and Platform Type Actuators Based on the Design Depicted in figure 6.

5 Sensors based on conducting polymers

CPs or intrinsically conducting polymers (ICP) are organic polymers that are electronically conductive with relatively high and reversible ion storage capacity. The mechanisms of both mechanical sensing and actuation are similar and based on the insertion and expulsion of ions into and from the polymer structure the structure itself being ionically as well as electronically conductive [13]. Depending on external stimuli and the produced output, this kind of material can be used as an actuator or sensor. Two different configurations have been used for CP-based sensor devices. One is a free-standing film of CPs, which operates in an electrolyte. Another configuration is the trilayer structure, which is made of two CP layers at the top and bottom, with an electrically non-conductive separator layer between them. The separator layer, which is ionically conductive, works as an ion reservoir and also as an electrical insulator. Trilayer sensors with an electrolyte within a separator layer can function in air and do not need an external electrolyte.

CPs' ability to measure relatively large strains (10 times larger than typical piezoelectric sensors) and their low mechanical impedance (Young's modulus) makes this kind of sensor potentially useful for multiple applications such as instrumentation to detect strain and force [14]. Additionally, tensile strain can be measured by a free-standing film of CP.

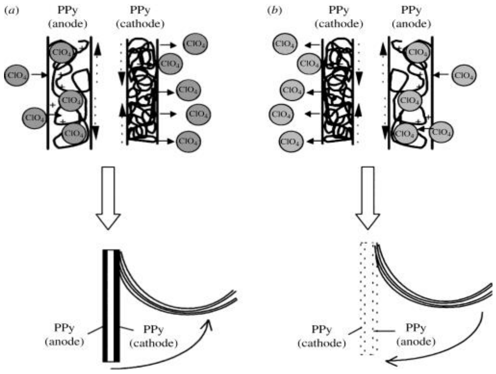

Fig8: tri layered cp

6 Sensors based on carbon nanotubes

Application of voltage to carbon nanotube electrodes immersed in an electrolyte results in charge to the electrodes. This charge is balanced by the counter-ions from the electrolyte. Insertion/expulsion of ions into/from the carbon nanotubes can generate positive and negative strain and enable carbon nanotube electrodes to work as an actuator. Inversely, doping carbon nanotubes with some molecules can produce a potential difference or change the electrical conductivity. Change in nanotube structures or change in electrical conductivity can be sensed and enable carbon nanotubes to be employed as sensors. Carbon nanotubes (CNTs) have drawn much attention due to their unique properties, including their one-dimensional nature, high stiffness and strength, thermal conductivity, ballistic transport and high surface area [105] .

Very large surface-to-volume ratio means the carbon nanotubes have high adsorptive capability: ideal for use in gas or chemical sensors. As the electronic properties of the nanotubes change with atomic structure and chemical doping, they are suitable for sensor miniaturization while maintaining high sensitivity.

7 Artificial muscle

Despite the tremendous engineering research opportunities in the development of soft actuators for robotic applications. The advent of EAPs (electroactive polymers) recently constitutes an enormous impact on lingering development activity. There are a couple of reasons why the materials deserve keen attention from the robotic engineering field. First, they could provide rectilinear motions without any assistance from a complicated power train. Recognizing that a complicated power transfer mechanism creates bulky robots and it hampers accomplishing delicate missions, total elimination or partial reduction of the power train mechanism benefits expansion of robot application where precise operation is required. Besides, reducing the number of power transmission stages, of course, improves energy efficiency. Second, the inherent flexibility of polymeric materials offers many engineering possibilities for creating biomimetic machines. Acknowledging the fact that animals are naturally soft, more precisely their actuation devices are soft, development of the soft energy transducer should be one of the most important prerequisites for biomimetic robot operations .Although actuators made with the polymers seem to provide many advantages over the traditional electromagnetic actuators, there are still some controversies over the feasibility of actuators. Stability and durability issues of the material, when it is manufactured as an actuator, are the principal concerns of the contention.

7.1 Inflatable Structures

Pneumatic artificial muscles (PAMs, often called McKibben muscle) can be defined as contractile linear motion gas pressured engines. Their simple design is comprised of a core element that is a flexible reinforced closed membrane attached at both the ends to the fittings, acting as an inlet and an outlet. Mechanical power is transferred to the load through the fittings. When the membrane inflates due to gas pressure, it bulges outward radially, leading to axial contraction of the shell. This contraction exerts a pulling force on its load. The actuation provides unidirectional linear force and motion. PAMs can be operated underpressure or overpressure, but they are usually operated overpressure as more energy can be transferred. In PAMs, the force generated is related to the applied gas pressure, whereas the amount of actuation is related to the change in the volume. Therefore, the particular state of PAM is determined by the gas pressure and length [15]. The unique, physical configuration of these actuators gives them numerous variable stiffness , spring like characteristics: nonlinear passive elasticity, physical flexibility, and light weight [16]. Like biological muscles, they are pull-only devices and should be used in antagonistic pairs to give better control of the actuation. Using an antagonistic pair provides control of the actuator stiffness allowing a continuum of positions and independent compliances. Like a human muscle, stiffness can be increased without change in the angle at the joint, giving an actuator control of both its stiffness and compliance . PAMs, which are only one membrane, are extremely light compared to other actuators. Their power-to-weight ratio of 1 kW/kg was observed. They have easily adjustable compliance depending on the gas compressibility and varying force of displacement. PAMs can be directly mounted onto robot joints without any gears, eliminating inertia or backlash. They are easy to operate without such hazards as electric shock, fire, explosion and pollution.

The muscle consists of a gas-tight bladder or tube with a double helically braided sleeve around it. The change in the braid angle varies the length, diameter, and volume of the sleeve. BPAMs have been widely used for orthotic applications because their length–load characteristics are similar to those biological muscles, but, due to the lack of availability of pneumatic power storage systems and poor valve technology, the interest in McKibben muscles has slowly faded in the scientific community.

The Bridgestone Co. in Japan reintroduced the BPAMs for industrial robotic applications such as the soft arm, and Festo AG introduced an improved variant of PAM.

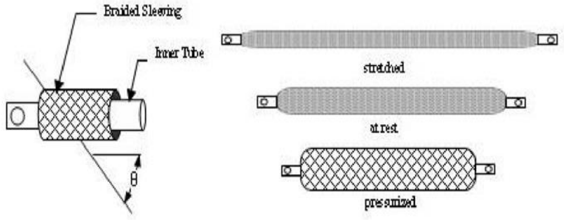

Fig9 Pneumatic Artificial Muscle

Most of the PAMs used are in anthropomorphic robots, but various weak points exist in the design of braided muscle.

They show considerable hysteresis due to the friction between the braid and shell, causing an adverse effect on the behavior of actuator, and a complex model is needed to determine the characteristics. PAMs generate low force and need an initial threshold pressure to generate actuation.

They are plagued by low cycle life, but their generated force, threshold pressure and life cycle are dependent on material selection. The wires in the sleeve also snap from the ends during actuation, and they have limited actuation capacity (20 to 30%). A new design of PAM called netted Muscle (ROMAC) was designed to have better contraction and force characteristics with little friction and material deformation, but they have complex designs[15]

8 Aviation technology

In aviation wing development is the major factor that affect aircraft stability. Inflatable wings have been in existence for decades and have found application in manned aircraft, UAVs,munitions control surfaces, and Lighter Than Air (LTA) vehicles. Recent system design challenges have ushered advances in the areas of materials, manufacturing, and configuration that have advanced this technology into a practical form for near term application. Inflatable wings can be packed into volumes tens of times smaller than their deployed volume without damaging the structural integrity of the wing. Deployment can occur on the ground or in flight in less than one second depending on the size of the wing and the type of inflation system used .Actuation of the aft end of the wing to achieve changes in section camber[5].

Several approaches have been developed that lend themselves to camber control via locally altering the geometry of the wing. Apart from use as a stand-alone aerodynamic surface on a small UAV, the inflatable assemblies can also be used as an aspect ratio increasing device on a larger aircraft to enable a more radical change in wing configuration .This approach serves to improve system efficiencies across changing flight regimes, allowing transitions from high speed target approach to low speed loitering.

Several actuation methods that are applicable to flexible structures have been studied and traded-off. Actuators with strong force generation capability (i.e. high blocked stress) can be added to inflatable structures to alter the length of the load bearing textile components of inflatable wings, thus altering overall shape. Performance requirements for such actuators were derived from a consideration of useful roll rate in a representative aircraft.

Other requirements were also compiled and include such items as high frequency response, ability to be folded and packed, low mass, low power consumption, and high cycle life. Morphing of an inflatable wing can be achieved using a technique called “bump flattening”, in which actuators are applied directly to the wing restraint. A piezoelectric actuator is bonded first to a rigid substrate, and then to the wing restraint fabric. When energized, a force is generated perpendicular to the plane of the actuator, resulting in a flattering of the individual bumps caused by the wing spar spacing. By flattening individual bumps in series, a net increase in run length is generated, resulting in deflection of the wing’s trailing edge[7].

One of the most promising morphing configurations for near term application was found to be a series of trailing edge actuation devices. This approach modifies a baseline inflatable wing configuration with PZT actuators that flex the trailing edge of the wing. Unlike ailerons however, the actuators reside under the wing skin, presenting an uninterrupted surface to the air stream .The actuators were considered in both unimorph and bimorph configurations. In the bimorph configuration, two MFC actuators from Smart Material were bonded to a metallic substrate. The actuators expand or contract in response to the application of a positive or negative voltage12. By applying opposite polarity voltages to the upper and lower actuator, the substrate is caused to flex. Investigations were conducted to assess the performance of several actuator configurations, in addition to the bimorph configuration just discussed. For each configuration, the actuator was set up as a cantilever, with one end clamped to a table top, and the other end free to move. The actuators can operate with a range of voltages from –500 VDC to + 1500 VDC.

For the case of the bimorph configuration, a single power supply was used with a voltage dividing circuit arranged to provide a maximum of +1500 VDC to one actuator while applying –500 VDC to the other. Due to the nature of the actuators, current draw is negligible. Voltage was applied to the actuator with the polarity such that the free end of the actuator curled up from the table top. With the actuator so energized, a gauge was used to measure the force required push the free end flat to the table

The actuators are attached to the upper surface of the wing, extending rearward and terminating at the nominal trailing edge location (Fig. 10). The actuators are arranged with span wise gaps to facilitate folding and packing of the wing. Upon application of a voltage, the actuators curve upward or downward, depending on the polarity of voltage applied. When the voltage is removed, the actuator returns to its nominal un-deflected position. On the development unit, an elastic fabric was stretched from the trailing edge of the upper wing surface to the trailing edge of the lower wing surface to enclose the actuators, suggesting how the actuators could be covered by a skin. Together, the actuator and elastic fabric provide a sharp trailing edge to the wing. An alternate configuration is possible, with an actuator attached to both the top and bottom surface, instead of just the top. This could potentially increase the amount of force available for deflection[6].

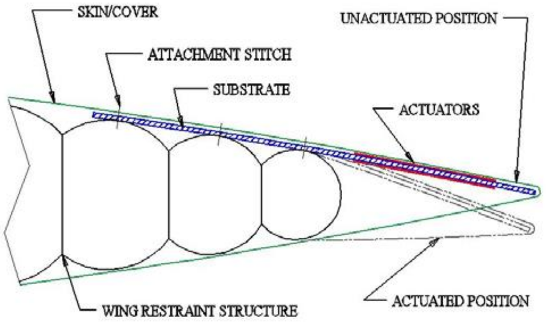

Fig 10: Trailing Edge Configuration

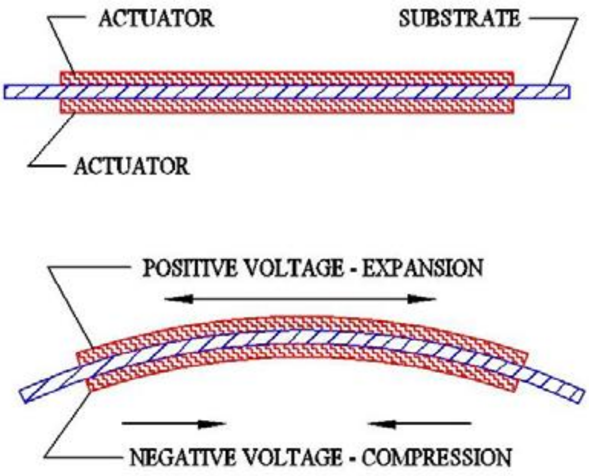

Fig 11 : Mechanism of actuator

9 Planetary sciences

EAP are the materials that can provide a new dimension to the applications of the polymers in the various industries on Earth but they are also being researched for the applications outside our Earth and that is where their extremities are being tested and enhanced. Space exploration and planetary sciences are the domains where materials and instruments are to be realized and enhanced to their extremes to get the most usefulness of the materials. It sometimes requires years to realise and a heavy finance to synthesize materials. But EAP provides an advantage over both these issues as they are easy to synthesize and they require less money.

Space environment is challenging for the EAPs especially in extreme high and low temperatures. EAPs such as polyaniline (PANi) and various types of gels can sustain temperatures up to 200ºC (in degraded performance and shielded state). But still some dielectric elastomers, conductive polymers and shape memory alloys sustain in these environments. EAPs are basically used in actuators, but there are some more upcoming applications of them being used as sensors, detectors and its biomimetic being used for the astronauts.

9.3 Robotic arms

Robotic arms used in the space applications generally have mechanisms or actuators or customized servo motors. But such structures are heavy, bulky and costly and occupy volume. Integrating such structures and mechanisms with the satellites and spacecrafts increase the load and consequently the cost of launching increases. But instead of using heavy and bulky mechanisms, an artificial muscle mechanism provides the required power as well as reduction in weight. They are easily customisable; as per the directionality of the force and displacement as well as locomotion. The response time of such mechanisms is less and better than the conventional methods. They operate on much less voltage and current ratings. Such robotic arms are very useful in cleaning space debris and satellite parts.

9.1 Exercise actuator

Exercise actuators are very much similar to the robotic arms but their much use can be made in the leg artificial muscles. This actuator basically replaces the motor or mechanical parts of the various exoskeletons of the legs which are under development in industry. These exoskeletons would replace the conventional exercising machines on board of spacecrafts for astronauts in space. This is to solve the major issues related to inactivity of the leg muscles due to micro gravity in space. The conventional exoskeletons are mounted on walls of the spacecraft but if EAPs are used then the reduction in weight and size of the exoskeleton would make it wearable to astronauts and would provide a continuous exercise to the muscles of the legs without interruption of anything.

Many of the Aerospace companies and agencies are making space suits and exoskeletons aiming at the interplanetary missions but most of the agencies have not revealed their real structures. NASA revealed its exoskeleton in its developmental state in its suit form which weighs around 25.85 kg (57lb). But this weight can be reduced further developed with use and enhancement of the EAPs. If EAPs prove their stability in the harsh atmospheres of the other planets, space and Moon then they can be integrated in the space suits as well. These exercise actuator integrated exoskeletons are not only useful in space but they will help some of the people on Earth for the first time.

9.2 Observation and sensing

EAPs require electric, pneumatic, chemical, optical and magnetic activation mechanism along with some low value of voltage for the deformation to take place. For application of the various EAPs we need to give these stimuli externally to produce deformation. But the magnitude and nature of these stimuli can be found out from the deformation or the changes in the polymeric structure. This makes the EAPs being used as sensors and to record observations.

The electro active polymers (EAP) are classified into various types due to their activation stimuli’s nature. The ferroelectric polymers produce strain when an electric field is applied to them. So these polymers can be used to measure the magnitude as well as nature of the electric field just measuring the strain in the polymeric material. The only condition on such applications is that the strain and the corresponding electric field magnitude and nature must have a standardised relation between them. The dielectric EAPs, IPMC (Ionomeric polymer – metal composite), graft elastomers EAP and Electro – Viscoeleastic elastomers are also some of the EAPs which respond to the electric field but their operating voltages, operating temperature range and sensitivity to the electric field are different which provides huge band of materials for the sensing of the electric fields.

The ionic electro active polymers (EAP) are the polymers which require a fluid for their activation. This activation fluid is different for different polymers and every polymer responds differently to different fluids. Thus EAPs can be used to detect the chemical elements present in the fluid and approximate the properties of the various complex composition fluids. This requires only a single test bed instead of many as per conventional techniques. The EAPs which use water as activation solvent are very much useful for realising moisture detecting sensors for the plant nurseries or even in new techniques used in making small greenhouses. These could also be used to realise a soil bed for the plants which can actuate the orientation of the bed as per the moisture content in the soil so that every plant is able to absorb moisture.

NASA is studying the electrostatic interaction between the various polymers and the micrometer sized particles. This study is very much important because such particles are found in the Martian dust storms which are very much frequent on Mars and sometimes they cover the whole planet and last long for many days to weeks. The problem of this interaction is that it produces a significant amount of voltage in polymers which can interact with sensors which they are protecting. NASA along with JPL working on this project at JSC (Johnson's Space Centre) where a approximate sample of Martian soil sample is made and wind speeds similar to the Martian dust storms can be generated. Now, the important thing is that they are testing new polymers and in near future they need to turn to the testing of the EAPs. EAPs also have the capability to turn off this interaction by interchanging the voltage generated into some other form of energy. If EAPs prove their capability it would open a new dimension in planetary missions.

9.4 Mirrors

Mirrors are one of the most integral parts of the planetary sciences. They play a key role in the telescopes which are used in the research of the cosmos. Mirrors are conventionally made of glass. But the diameter of such mirrors is limited and the time required the manufacturing of the glass mirrors ranges from some months to couple of years. So to tackle these issues there are some techniques such as using inflatable mirrors. These inflatable mirrors are actuated by EAPs or the EAP itself can be made as a mirror by making one surface of the polymer reflecting. For using EAPs in the mirrors, they are needed to be enhanced to a great extent.

10 Other Developments

The EAP is a new dimension in material science and every domain of the industry takes efforts to make benefit of its hybrid properties. The applications discussed above are some of the important ones. But there are some other applications of the EAP. They are listed below:-

- EAPs are used in the development of a bird- like plane which can harness energy from sun and fly and glide in air like birds. These can easily replace the drones and can be used surveillance.
- EAPs are the potential materials for the drug delivery systems in bio medical field as they can deliver drugs at accurate targets and in required quantities.
- They are useful in manufacturing of light weight prosthetic parts which can change lives of many people.
- Electrochromic polymers are the new EAPs which change colour according to their activation mechanism. They are used in various types of indicators.
- EAPs are being researched for the development of the smart clothes and smart textiles.

11 Challenges

- For the realisation of the EAPs for the planetary applications, the effect of the extremes levels of the radiation on their structures and properties must be researched accurately.

- The EAPs used till present are often used encapsulated in space, so development is required to use them directly.
- In planetary applications the life time of the materials required is very vast and in extreme environments, which is very difficult in case of EAP.
- EAPs used made of organic molecules are harmful for interplanetary missions as it is against the code of conduct of the astronomical community.
- Standardisation of the various graphs of properties of EAPs is required to be used for sensing purposes.

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