A Review on Electroactive Polymers Development for Aerospace Applications

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2 authors:

Musavir Bashir
Universiti Sains Malaysia

Parvathy Rajendran
Universiti Sains Malaysia

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A review on electroactive polymers development for aerospace applications

Musavir Bashir and Parvathy Rajendran

Abstract

Newfangled smart materials have inspired the researchers to look for more efficient materials that can respond to specific stimuli and retain the original shape. Electroactive polymers are such materials which are capable of sensing and real-time actuation. Various electroactive polymers are excellent candidates due to high strain rate, fast response, reliability and high mechanical compliance despite tough manufacturing. In this study, electroactive polymers are reviewed and the general enabling mechanisms employing their distinct characteristics are presented, and the factors influencing the properties of various electroactive polymers are also discussed. Our study also enumerates the current trends in the development of electroactive polymers along with its progress in aerospace discipline. The electromechanical properties of electroactive polymer materials endow them the capability to work as both sensors and actuators in the field of aerospace. Hence, we provide an overview of various applications of electroactive polymers in aerospace field, notably aircraft morphing. These actuators are vastly used in aerospace applications like Mars Nano-rover, space robotic, flapping wings and active flap. Therefore, the electroactive polymer applications such as effective actuators can be investigated more in their materials, molecular interactions, electromechanics and actuation mechanisms. Considering electroactive polymers unique properties, they will endeavour the great potential applications within aerospace industry.

Keywords

Electroactive polymer, ionic polymer–metal composite, dielectric elastomer, space, aircraft morphing

Introduction

Electroactive polymers (EAPs) have a mechanical response to electrical stimulation. This ability to respond on any change in the ambience of animate or inanimate system is called actuation. They are compliant work producing systems (Bystricky, 2012; Moreau, 2007; Nguyen et al., 2012; Ricotti and Menciassi, 2012; Zupan et al., 2002) and are based on numerous physical principles manifesting diverse performance capabilities (Brauer, 2006; De Rossi et al., 2005). EAP actuators are now widely used because of their numerous actuation modes, high actuation strain and biomimetic ability (Bar-Cohen, 2004a; Carpi and De Rossi, 2005; Tondu, 2007).

Various EAPs show large strain and high-speed electromechanical response when subjected to electrical stimulation, therefore mimicking the natural muscles (Bar-Cohen, 2011; Meijer et al., 2003). Therefore, EAP materials are named as ‘artificial muscles’. Meanwhile, several different mechanisms can determine their response to electrical stimulation. EAP and its composites have ability to morph (adopt) to shape change in response to suitable stimulus, such as external electrical, magnetic, chemical or thermal stimuli (Oliver et al., 2016; Pons, 2005; Samatham et al., 2007; Sun et al., 2012).

In case of McKibben artificial muscle, the maximum force-to-weight ratio can be surprisingly high for a limited radial dimension and for a conventional pressure regime. A 50-g McKibben muscle can easily develop more than 1000 N under 5 bar weight for an external radius varying from 1.5 to 3 cm (Tondu and Lopez, 2000). Haines et al. are building up another class of artificial muscles produced using highly twisted fibres of different materials, extending from exotic carbon nanotubes to normal nylon string and polymers. Such muscles are termed as actuating fibres ‘artificial muscles’

School of Aerospace Engineering, Universiti Sains Malaysia, Pulau Pinang, Malaysia

Corresponding author:
Parvathy Rajendran, School of Aerospace Engineering, Universiti Sains Malaysia, 14300 Nibong Tebal, Pulau Pinang, Malaysia.
Email: aeparvathy@usm.my

Table 1. Classification of EAPs (Bar-Cohen and Zhang, 2008; Biggs et al., 2013; Jo et al., 2013; Rajan and Gladis, 2016; Wang et al., 2016).

EAP type	Additional actuator types	Actuation mechanism	Activation voltage	Response time	Example
Electric polymer	Ferroelectric polymers	Piezoelectricity	>1 kV	Fast	Poly(vinylidene fluoride) (PVDF), P(VDF-TrFE)
	Dielectric polymers	Electrostatic field force	>4 kV	Fast	Silicon elastomer, polyurethane
Ionic polymer	Conductive polymer	Electrochemical process	1–5 V	Slow	Polypyrolle, polyaniline
	IPMC	Electrode-ion transportation	<3 V	Slow	Nafion, Flemion
	Ionic polymer gels	Ion-diffusion via polymer gel	<1 V	Slow	Polyvinyl alcohol

EAPs: electroactive polymers; IPMC: ionic polymer–metal composites.

since they mimic the fibre-like form factor of natural muscles. While the name summons the possibility of humanoid robots, they are interested for their potential use for other reasonable applications, for example, in cutting edge intelligent textiles (Haines et al., 2016).

Morphing can also be defined as ability to adopt to the ambient conditions and it may involve micro or macro and structural or fluidic approaches (Gohardani et al., 2014; McEvoy and Correll, 2015; McGowan et al., 2002b). This adeptness is of great significance in fields such as biomedical, structural health monitoring, aerospace, defence and robotics (Jani et al., 2014; Le et al., 2015; Nguyen et al., 2012; Sassone et al., 2016; Siciliano and Khatib, 2008). Biomimetic applications are one of these interested fields because of the ability of EAP materials to mimic the movements of insects, animals and humans for making biologically inspired mechanisms (Bar-Cohen, 2006; Habib, 2011; Mutlu et al., 2016; Oliver et al., 2016; Vedaraj et al., 2012).

The electromechanical properties that some EAP materials have enable them to work as both sensors and actuators (Bar-Cohen and Zhang, 2008; Biggs et al., 2013; Jo et al., 2013; Rajan and Gladis, 2016; Wang et al., 2016). Ionic EAPs and electronic EAPs are two broad classifications of EAPs. Ionic EAPs are stimulated by the migration of ions or molecules. Some of the examples of such EAPs are conducting polymers and ionic polymer–metal composites (IPMC). Similarly, electronic EAPs such as dielectric elastomers (DE), electrostrictive polymers and piezoelectric polymers are activated by applied electric fields. The classification along with material examples is illustrated in Table 1.

Being the substance of this study, EAP actuators are expected to be light, compact and operated at low-power conditions (Asaka and Nakamura, 2014; Bar-Cohen, 2004c; Bar-Cohen et al., 2000; Carpi, 2014; Hanson, 2013; Tung et al., 2001). These requirements are generally needed for future NASA missions to develop robotic arms, rovers, morphing unmanned aerial vehicles (UAVs), efficient wings and so on (Bar-Cohen et al., 2000). Smart material technology has offered a variety of materials with competitive characteristic properties like reduction in size, mass and power consumption, actuation rate and ease of manufacturing (Jani et al., 2014; Monner, 2005; Priya, 2007; Spencer et al., 2004). EAPs are emerging as suitable materials with these abilities that cannot be paralleled by the counterparts (Kornbluh et al., 2004b). Table 2 depicts the comparison between the proficiency of EAPs with other smart materials.

There are many worthwhile literature introspects, surveys available in the development of EAPs and its composites. Bar-Cohen and Zhang (2008) gave a summary of contemporary EAP and their potential applications as actuators and sensors. They also discussed on EAP actuators employed in aerospace industry and showed the future challenges in their development (Bar-Cohen, 2000). Spinks et al. (2003) showed the use of EAP actuators and their importance to introduce new actuation materials by employing new approaches in the rehabilitation glove technique.

Punning et al. (2014) carried out large-scale study in the performance of several ionic EAP (i-EAP) actuators in space applications. The results demonstrated that EAP actuators are fully tolerant to the ionizing gamma and X-ray radiations in space. In addition, Ren et al. (2016) investigated the thermal response of a hybrid actuator composed of an EAP and shape memory polymer (SMP). It was manifested that the thickness ratio of the EAP/SMP films plays a critical role in the displacement of the actuator and shows a great promise for future morphing applications.

DeMauro et al. (2015) employed EAP actuator in controlling the flow over an airfoil in order to mitigate the separation bubble. The design of EAP actuators was quantified to meet the requirements of flow control mechanism. Kruusamäe et al. (2015) reviewed an article associated with self-sensing ionic polymer actuators by investigating conducting polymer actuators (CPAs), IPMC and carbonaceous polymer laminates.

Guarino et al. (2016) presented an analysis on EAPs manifesting great promise as biomaterials acting as an interface between electronics and biology. He concluded that it is due to the highly tenability of chemical/physical properties which confer them different

Table 2. Efficiency of EAPs with other smart materials (Bar-Cohen, 2001b, 2004b).

Property	EAP	Shape memory alloys (SMA)	Electroactive ceramics
Actuation displacement	>10%	<8% short fatigue life	0.1%–0.3%
Force (MPa)	0.1–3	About 700	30–40
Reaction speed	μ to s	s to min	μ to s
Density	1–2.5 g/cm^3	5–6 g/cm^3	6–8 g/cm^3
Drive voltage	4–7 V	NA	50–800 V
Power consumption	M-Watts	Watts	Watts
Fracture toughness	Resilient, elastic	Elastic	Fragile

EAPs: electroactive polymers.

conductive properties for various applicative uses (i.e. molecular targeting, biosensors, biocompatible scaffolds). Qian et al. (2015) give an extensive study on poly(vinylidene fluoride) (PVDF)-based ferroelectric polymers as multifunctional EAPs and presented the analysis on the characteristics properties like electrocaloric effect, giant electro-actuation and large hysteresis-free polarization response.

Although many researchers offer valuable investigations in the field of EAP, the application of EAPs in aerospace, particularly aircraft applications, has not been examined as per their potential. This review is expediently enumerated and aimed at contributing to cutting edge technologies in aerospace, especially aircraft morphing structures. It can be strongly articulated that EAP actuators will play a significant role in aerospace in the future. Using EAP actuators, various novel mechanisms and devices have already been demonstrated, including robot fish, catheter steering element, miniature gripper, drag reducing materials, active diaphragm and dust wiper. The impressive advances in improving their actuation strain capability are attracting the attention of engineers and scientists from many different disciplines. Therefore, these features make them a strong candidate for aerospace applications, including aircraft morphing.

Recent trends and advancement

The new trend research is to recognize EAP material improvements and new advancement to increase the understanding of their behaviour, including their physical chemistry and fabrication processes. In the past decade, significant progress has been accomplished in academic and commercial disciplines of EAPs as newfangled smart materials (Hu et al., 2012; McGowan et al., 2002a; Wallace et al., 2008; Ward et al., 2015).

EAP materials have good adaptability, compactness, good control over the system, quick response time, low power consumption, comparatively reduced raw material costs and relatively low manufacturing costs (Anderson, 2011; Bar-Cohen, 2005; Reece, 2007; Vogan, 2004; Wang et al., 2016). Because of these characteristic properties, they have taken the place of electric motors in the structure (Madden, 2007). EAP-conducting polymer trilayers were obtained for fast actuation by reducing the thickness of the device to as much as 6 μm (Takalloo et al., 2017). Palmre et al. (2014) reported a first nanostructured electrode surface design for IPMC comprising platinum nanothorn assemblies with multiple sharp tips, which resulted in a dramatic improvement (threefold to fivefold increase) in both actuation range and blocking force at low driving voltage (1–3 V).

This material has unique features that are empowering many new technologies. The distinct features include the capability to undergo enhanced displacements than almost any other class of smart materials; the flexibility required for biomimetic and other structural systems, low density (Bar-Cohen, 2001a; Segev-Bar and Haick, 2013) and mimic natural muscles (Bar-Cohen, 2005) enabled them to be employed as both actuators and sensors (Table 3).

Table 3 shows various performance indices, among which few are defined. One of the more useful metrics for comparing actuator materials, independent of size, is the energy density of the material. The actuator energy density is the maximum mechanical energy output per cycle and per unit volume of material. The coupling efficiency, k^2, is termed as the electromechanical coupling factor which is defined as follows: k^2 equals energy converted into mechanical work per cycle/electrical energy applied per cycle. It provides the assessment of dynamic actuation efficiency of actuators, like unimorphs and double-layer bimorphs bending actuators. Actuator efficiency is the ratio of mechanical work output to energy input during a complete cycle in cyclic operation. Actuator density is the ratio of mass to initial volume of an actuator.

Advancement of effective and powerful mechanisms and devices that are actuated by EAP materials needs enhanced understanding of their behaviour, design concepts for efficient actuation, generation and sensing and reliable and repeatable fabrication and characterization methods, as well as effective control algorithms and electronics (Bar-Cohen, 2017; Bundhoo, 2009; Kaasik et al., 2017; Mengmeng et al., 2017; Rus and Tolley, 2015; Wang et al., 2016; Wilson et al., 2007). The

Table 3. Actuation capability of electric EAPs and natural muscles (Pelrine et al., 2000; Saliterman, 2006).

Actuators type	Maximum		Specific elastic energy density (J/g)	Elastic energy density (J/cm^3)	Coupling efficiency k^2 (%)	Maximum efficiency (%)	Specific density	Relative speed (full cycle)
	Strain (%)	Pressure (MPa)						
DE artificial muscle – silicone	32	1.36	0.22	0.2	54	90	1	Fast
DE artificial muscle – polyurethane	11	1.6	0.087	0.087	21	80	1.1	Fast
P(VDF-TrFE)	4	15	0.17	0.3	5.5	–	1.8	Fast
Electrostatic devices	50	0.03	0.0015	0.0015	50 (est.)	>90	1	Fast
Electromagnetic (voice coil)	50	0.1	0.003	0.025	N/A	>90	8	Fast
Piezoelectric – ceramic	0.2	110	0.13	0.1	52	>90	7.7	Fast
Piezoelectric – single crystal	1.7	131	0.13	1	81	>90	7.7	Fast
PVDF	0.1	4.8	0.0013	0.0024	7	–	1.8	Fast
Shape memory alloy	>5	>200	>15	>100	5	<10	6.5	Slow
Shape memory polymer	100	4	2	2	–	<10	1	Slow
Thermal (expansion)	1	78	0.15	0.4	–	<10	2.7	Slow
Polyaniline	10	450	23	23	<1	<1	~1	Slow
Polyelectrolyte	>40	0.3	0.06	0.06	–	30	~2	Slow
Magnetostrictive (Terfenol-D, Etrema Products)	0.2	70	0.0027	0.025	–	60	9	Fast
Natural muscle (human skeletal)	>40	0.35	0.07	0.07	N/A	>35	1	Medium

current accomplishments and challenges in the field of EAP are noteworthy (Asaka and Nakamura, 2014; Biggs et al., 2013; du Toit et al., 2016; Vinogradov et al., 2005). Kaneto (2016) has shown that the research trends of EAPs and conducting polymers characteristics as given in Table 4.

Currently, EAPs are widely employed in different categories, like IPMC, conducting polymers, DE, gels and carbon nanotubes (Leng, 2012; Schoen and Ebrahimpour, 2013). The driving techniques of IPMC, known as a material for simulated muscle actuators, are not studied much. Jung and Nam (2003) inferred that large consumption of current amid actuation is caused by the high-frequency components of the driving waveforms because the IPMC actuator has the characteristics of damped high-pass filter. A distinct actuator based on soft polymer was developed based on the volume change of a conducting polymer. The linear elongation (12 % at a load of 0.5 MPa) revealed is the highest yet for a centimetre-scale CPA (Bay et al., 2003).

Now the progresses in these materials have turned them multifunctional and distinct from their original properties. Figures 1 and 2 illustrate a literature survey carried out on second week of May 2018 using the Web of Science and Scopus database with search key words of EAPs within aerospace disciplines. Each mentioned keyword was used in the search dialogue and resulted papers were count listed by year and presented and compared in the given bar graph. The research activity of EAP actuators has increased but the growth in the literature is not satisfactorily mainly because the range of applications and advancements are not familiar to all users.

Markets for EAP devices are strongly impelled by the progressing research in biomedical field (Bar-Cohen et al., 2009; McDaid, 2011, 2014), electronics and robotics (Bar-Cohen et al., 2009; Van der Loos and Reinkensmeyer, 2008), with its demand for a new class of electrically controlled actuators based on polymer materials. The growing EAPs in different commercial sectors are depicted in Figure 3. The global market for EAPs is projected to reach 725.8 million pounds by 2021, up from 484.9 million pounds in 2016, reflecting a 5-year compound annual growth rate of 8.4% (BCC Research LLC, 2016).

General mechanism of EAPs

There are numerous active polymers with distinct controllable properties because of the diverse activation phenomena (Bar-Cohen, 2001a; Liaw et al., 2012). In these smart materials, both one-way activation and reversible activation are seen, depending upon the integration of smart structure (Elzey et al., 2005; Kornbluh et al., 2002; Michaud, 2004; Sofla et al., 2007). The

Table 4. Characteristic properties of conducting polymers (Kaneto, 2016).

Property	Minimum	Typical	Maximum	Limit
Strain (%)	1	3–9	>35	
Stress (MPa)		1–5	34	200
Work sensitivity (KJ/m^3)		70		1000
Strain rate (%/s)		1	11	10,000
Power (W/kg)			150	100,000
Life (cycle)		28,000	800,000	
Coupling			0.1	
Efficiency (%)		<1	18	
Modulus (GPa)	0.1	0.8	3	
Tensile strength (MPa)		5	120	400
Applied potential (V)		1.2	10	
Charge transfer (C/m^3)	10^7		10^8	
Conductivity (S/m)		10,000	45,000	
Cost (US$/kg)	3		1000	

selection of materials for the development of smart structures is based on shape control and self-sensing abilities (Tani et al., 1998). EAPs react to ambient changes like an electrical stimulus.

The various mechanisms through which EAPs produce actuation are polarization, mass/ion transportation, molecular shape change and phase change (De Rossi et al., 2004; Samatham et al., 2007). DEs and piezoelectric polymers produce actuation through polarization. Conducting polymers and gel polymers produce actuation basically through ion/mass transportation. Liquid crystal elastomers and SMPs produce actuation by phase change. Therefore, various stimuli such as electrical, magnetic and light can lead to the diversification of the applications of EAPs. Electrical stimulation is considered the most promising, owing to its availability and advances in control systems (Kim and Tadokoro, 2007). Tremendous amount of research is being done on the development of EAPs, but other kinds of stimulation have their own niche applications as well (Samatham et al., 2007).

Based on the stimuli and response, therefore, different EAPs have different actuation mechanisms (Bar-Cohen, 2001a; Brochu and Pei, 2010; Kim and Tadokoro, 2007; Vinogradov, 2008). Hence, based on their actuation mechanism, they are classified into two categories ionic EAPs, including IPMCs and CPAs, and field-activated EAPs, including ferroelectric polymers and DEs (Brochu and Pei, 2010; Shankar et al., 2007) and are illustrated in Figures 4 to 6 in respective order.

The phenomenon behind the ionic EAPs is based on the migration of ions triggered by a force resultant from the electric field (O'Halloran et al., 2008; Pugal et al., 2010). Generally, they require less voltage of around 10 V for their operation but suffer from low-frequency and low-energy efficiency (Kim and Tadokoro, 2007; Kornbluh et al., 2004a). On the other hand, higher electromechanical coupling efficiency of the field-initiated EAPs is specifically utilizing electric power (Kim and Tadokoro, 2007). Also, they have large response to the strain and have relatively shorter response time; however, much higher voltage is required to actuate them (Kim and Tadokoro, 2007; Madden et al., 2004).

Factors affecting EAP properties

Various EAPs have been developed ranging from fibres to films and fabrics are being employed in many disciplines including microelectronic and microelectromechanical systems (MEMS) technology (Castano and Flatau, 2016; Lampani, 2010; Schumacher, 2007; Sukhoveyev, 2008).

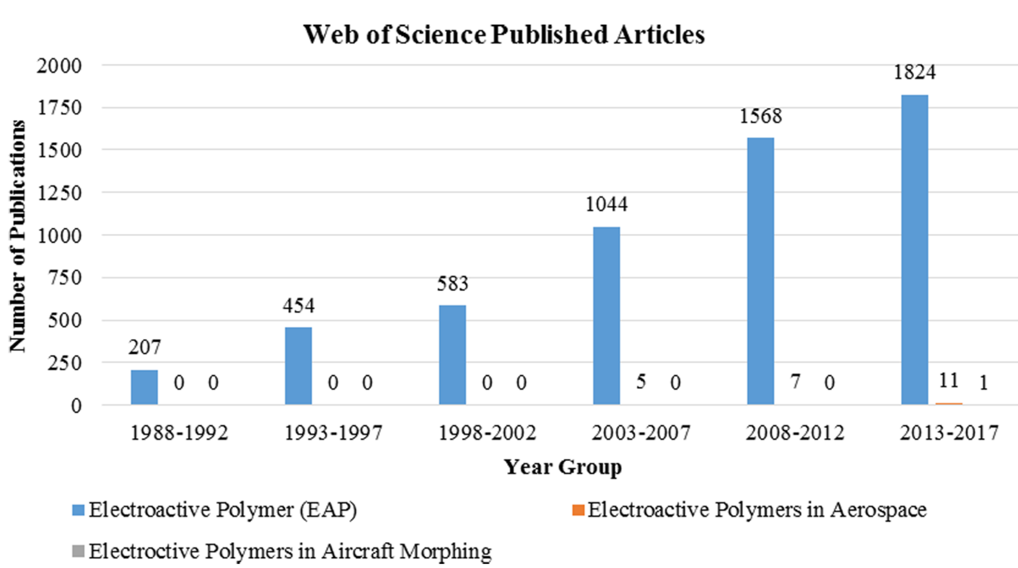

Figure 1. Number of EAP articles in different year groups.

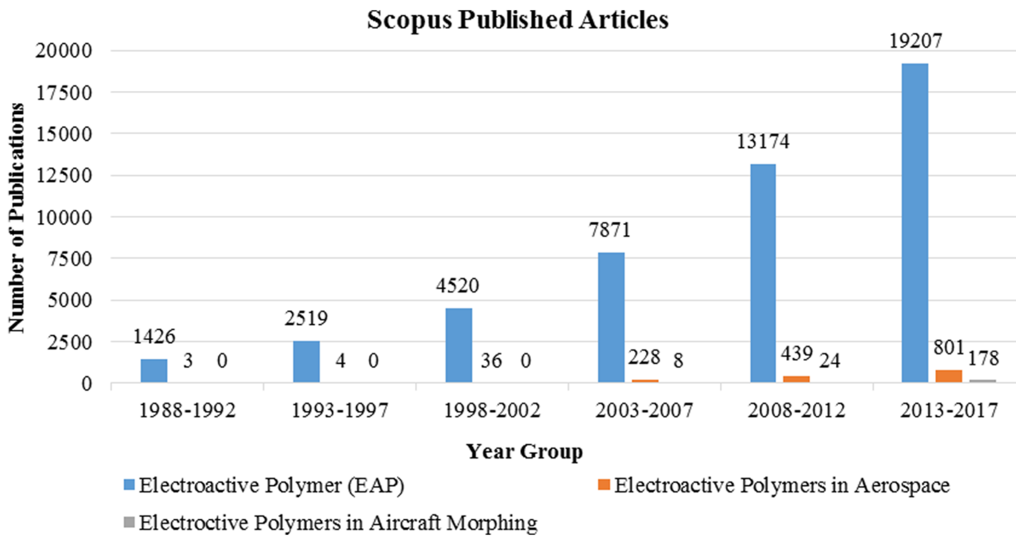

Figure 2. Number of EAP articles in different year groups.

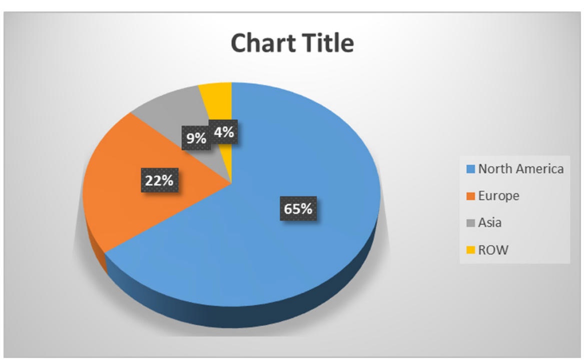

Figure 3. Global market forecast for EAPs in different regions (BCC Research LLC, 2016).

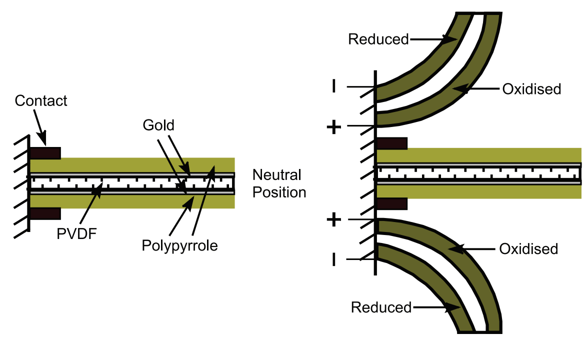

Figure 5. Schematic structure of the PPy trilayer actuator and schematic representation of the bending principle (Alici, 2009).

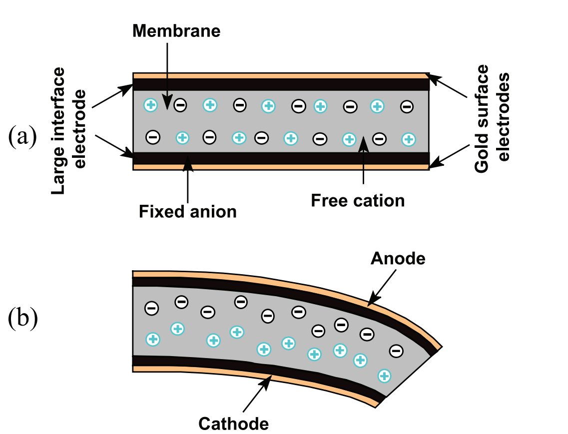

Figure 4. (a) A schematic representation showing the composition of an IPMC actuator along with the ions repartition in the membrane. (b) The IPMC deflects towards the cathode upon application of a voltage due to the accumulation of the free cations on the cathode (Najem and Leo, 2012).

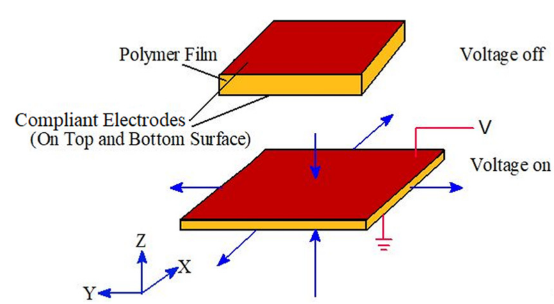

Figure 6. Schematic representation of DE actuation mechanism.

EAP-based actuators and sensors are showing continuous improvement in their mechanical flexibility, quality of signal output as well as fabrication techniques (Carpi and De Rossi, 2005; Gassert et al., 2006; Li et al., 2011). However, the research standards are yet to meet full expectations of various fields which require intensive consideration to investigate different mechanisms of these smart materials.

There are many factors that need consideration when understanding EAP properties; such as geometrical configurations, chemical composition of the materials, molecular interactions as well as fabrication processes. For example, CPAs are of interest in applications where low voltage and higher work densities are of interest (Shoa et al., 2008). Lower force generation and operational voltages make EAP preferences in many applications even with low life cycle, less energy conversion efficiency and needing large surface area electrodes to obtain high actuation rates (Kim and Tadokoro, 2007). Also, the association of different materials like copper phthalocyanine oligomer blended with silicones results in high dielectric materials (Bar-Cohen et al., 1999; Suo, 2010; Zhang et al., 2002). It should be noted that the dielectric strength of an elastomer film is one of the significant factors in actuator applications (Nam et al., 2007; Suo, 2010). The dielectric strength is reduced by integrating heterogeneous entities in the elastomer actuator, thereby affecting the actuator performance. In case of nanocomposite systems, the morphology of nano-platelets assesses their dielectric strength and modulus (Nam et al., 2004, 2007). A significant increase in the modulus of nanocomposite is observed by arranging the nanoplatelets uniformly in a polymer, along with a slight increase in dielectric constant.

The observed actuation modes of EAPs include elongation, contraction, bending, rotation and coiling, and therefore these factors that affect the characteristic features of all these EAPs should be studied (Bar-Cohen, 2001a; Kim and Tadokoro, 2007). For most ionic polymer actuators, a large reduction in the generated strain is observed with the increase in frequency, the decrease in voltage of the activation field or both, which hampers their use in practical applications (Kim et al., 2013). This situation restricts their use in practical applications. In addition, the competition within anion and cation actions in the ionic liquid also affects EAP's performance (Temmer et al., 2013). Deformation in conducting polymer actuation is achieved when the outer field leads to the flux of ions into or out of the polymer backbone. The variance in the ion composition sometimes causes solvent flux (Kim and Tadokoro, 2007; Larsson and Wimmerstedt, 1993). The insertion and removal of ions between polymer chains are considered the primary factor for deformation, whereas conformational change and solvent flux are considered secondary factors (Madden et al., 2004). The molecular chain orientation in the polymer affects the rate of ion transfer during oxidation. The higher orientation of polymer chains results in increased actuation response (Bay et al., 2001; Kim and Tadokoro, 2007). The performance of DE actuation is directly affected by the stiffness and dielectric constant of an elastomer (Nam et al., 2007; Suo, 2010). In terms of actuator strain, lower values of modulus and higher values of dielectric constant are recommended (Nam et al., 2007). But under stress conditions, the lower modulus values are not always recommended because the maximum stress attainable from an actuator increases with the modulus of elastomers.

Applications of EAPs in aerospace

The significant progresses of actuation strain capability of EAPs have been attracting engineers and researchers from different fields. The electromechanical properties of EAP materials endow them the capability to work as both sensors and actuators (Bar-Cohen and Zhang, 2008; Carpi and De Rossi, 2006; Jo et al., 2013). An EAP can be induced using electricity to make a significant change in shape or size, where the strain can reach up to 300% (Bar-Cohen, 2001a, 2002). EAPs possess many merits when considered as an actuator since they are lightweight, fast response, low power consumption, low actuation voltage and good flexible (Mazzone et al., 2003; Rao, 2014; Samatham et al., 2007).

Recently, i-EAP based on Nafion and Flemion have gained significant attention as newly developed sensor and actuator materials (Jo et al., 2013; Li et al., 2011; Shoji and Hirayama, 2007; Wang et al., 2009). The actuation performance was previously under investigation, and in some recent works, flexible tactile sensors based on composites of Flemion ionic polymer metal were also reported (Wang et al., 2009). An i-EAP actuators with large strain and low operation voltage have a promising future for applications such as MEMS and smart materials and systems (Knight et al., 2006; Li et al., 2011; Shahinpoor, 2001; Wallace et al., 2008).

Li et al. presented an architecture for fluid-driven origami-inspired artificial muscles, which can contract over 90% of their initial lengths, generate stresses of ∽600 kPa and produce peak power densities over 2 kW/kg – all equal to, or in excess of, natural muscle. This architecture for artificial muscles opens the door to rapid design and low-cost fabrication of actuation to large deployable structures for space exploration (Li et al., 2017).

Current research EAPs is converged in evolution of innovative actuator configurations and materials to provide improvised actuation properties. The recent breakthrough applications of EAPs in aerospace field have attracted a lot of attention. Visco-elastic EAP materials could provide more lifelike aesthetics, vibration and shock dampening and more flexible actuator designs (Nguyen et al., 2014). EAPs incorporate a class of encouraging materials for sensing, yet are still new to most specialists taking a shot at sensor-related subjects, as till now there is no material that can cover all sensory requirements. Possible tasks involve assembly, repair, refreshing, re-circling or deorbiting, spacecraft discharge and recover, space traveller functioning support, assessment and refuelling.

Moreover, much research has been directed on printed electronics, and there has been generally little effort on printed mechanical actuators. EAPs are a promising class of materials for such printed parts since they can be solution processed. IPMCs are especially encouraging owing to the substantial bending strains that can be accomplished at low voltages. IPMC actuators operate by the movement of ions within a membrane that is an ionic conductor. In-depth understanding of the ion transport and storage under electrical stimulus is a key point in optimizing the actuator performance. In comparison, applications such as MEMS, large-scale antennas, smart materials and systems, morphing aircraft skin and energy harvesting are highly in need for solid-state electromechanical actuators with large strain, high elastic energy density and low operation voltage.

Space applications

The interest in the development of several robotic systems and experiments for space operations resulted in many investigations. Flores-Abad et al. (2014) give a comprehensive introspect of space automated advances and applications to OOS (on-orbit adjusting), few of which will be outlined here. Three expansive robotic frameworks equip the International Space Station (ISS) for assembly, repairing and astronaut support purposes: the Canadian Space Agency (CSA) built up the Space Station Remote Manipulator System (SSRMS); the Japanese Experiment Module Remote Manipulator System (JEMRMS) was worked by the Japan Aerospace Exploration Agency (JAXA); the European Robotic Arm (ERA) is given by the European Space Agency (ESA). German Space Center (DLR) built up a few space robotic analyses to be tried on-board the Space Shuttle or the ISS, including a human robot called Space Justin like Robonaut by NASA. It was concluded that there are still many challenges in the development of space robots and other space technology equipment which can be accomplished by the advanced research in smart materials, including highly promising EAPs.

One of the prominent design requirements for space missions is that they should be easily deployable and controllable without serious failures. Large size, bulky materials can limit the mission capabilities, whereas lightweight, compact and unsophisticated energy-effective technologies enable missions to spend more time in space, travel farther and explore new destinations (Freitas and Gilbreath, 1982; Larson and Wertz, 1992; Yoshida et al., 2014). Research towards promising space-affiliated technologies has approved two principal classes of EAPs: dielectric and ionic. The category of i-EAPs is one of the suitable candidates, meeting all standards for the desired technologies (Asaka and Okuzaki, 2014; Romasanta et al., 2015).

The i-EAP actuators are capable of large bending stroke to a low-voltage signal without requiring rotating parts, shafts or precautions against friction (Punning et al., 2014). An i-EAP actuator can sense motion or moisture, harvest energy and store electric energy as a supercapacitor, and the same portion of the laminate can perform several different functions (Punning et al., 2014). Due to the prominent features, ample i-EAP–based spaceworthy devices have been proposed during the past decade.

However, the researchers are aiming an all-in-one actuator, sensor and absorber material. EAPs have promised to behave as such materials for space operations, specifically IPMC. Since the research has shown that the material needs to be humid in order to bend, abridgement of the IPMC is crucial (Bhandari et al., 2012). The functional capability of IPMC in vacuum and temperatures as low as −140°C has been verified.

Despite the potential and promising applications in space robotic and automation, a great effort is still needed. An example worth mentioning is MUSES-CN Mission, in which a Nano-rover was supposed to be sent to space. The investigating project was employing IPMC as dust wiper on the infrared camera window (Ghamsari, 2012; Starek et al., 2016; Tsumaki et al., 2012). It was a promising idea because the functionality of IPMCs at low pressure and low temperature was previously verified.

Recently, the ESA attempted to launch space-based projects that approved companies to investigate the manufacturing techniques and the control capability of fully integrated smart materials at preliminary levels of space components (Feranec et al., 2016; Punning et al., 2014). In these projects, several results were obtained towards the control techniques in designing and manufacturing of different smart materials. Also, the functional and operational requirements for future space missions were also addressed.

Several technologies developed in many stages included large membrane structures, deployable structures and inflatable structures. Inflatable structure offer a very promising opportunity for realizing large structures by keeping mass and volume very low, offering a very good storage capability in the room available on board the space transportation systems (McGowan et al., 2002a). Unfortunately, membrane structures encounter instability phenomena that could seriously endanger the mission, as demonstrated by a NASA flight experiment, where the dynamics of the structure was completely out of control (McGowan et al., 2002a).

The participating space agencies in ISS are conducting programmes which include advanced life support in space, cardiovascular alterations, human behaviour and performance, muscle changes, radiation effects and so on, with smart material technology like IPMC. The EAPs are seen as the promising technology to overcome all these challenges for the future. DE actuators have also been investigated by Stanford Research Institute for shape control of lightweight space mirrors (Carpi et al., 2005).

A project undertaken from NASA Institute of Advanced Concepts, some researchers at MIT developed a lightweight hyper-redundant manipulator based on DE actuators, and a prototype, Binary Robotic Articulated Intelligent Device, was successfully tested (Fontaine, 2002). Inflatable reflective structures were integrated with actuation elements and external linear actuators were also employed in this study.

Aircraft morphing applications

An investigation of the thermal response of a hybrid actuator obtained by integrating EAP and SMP has been carried out (Ren et al., 2016). This is induced by the change of temperature in a P(VDF-TrFE) film to tune the shape of an SMP film above its glass transition temperature. Here, the thickness ratio between EAP and SMP film and temperature play a critical role in the displacement of the actuator. Moreover, finite element method simulation results and the measurement data fit well together. This structural feasibility is a great promise for future morphing aircraft applications.

EAPs have been employed in flapping wing micro air vehicles (MAVs) (Anderson, 2011; Anderson et al., 2011; Baker et al., 2012; Burgess et al., 2009; Conn et al., 2006; Duggan, 2000; Pawlowski et al., 2003; Sun et al., 2016). One such investigation verified a sinusoidal signal that needed to produce sufficient lift from the flapping wings for the MAV to become airborne was only 2.5–4 V (Duggan, 2000). Furthermore, the motor-driven actuators are not suitable for mimicking the flapping motion of wings. It will be fascinating to employ micro-robots to create flapping flight, and EAP is the most suitable candidate for such actuators (Kim and Tadokoro, 2007; Schenato et al., 2003; Yan et al., 2001) because of its light weight and high deformation rate that enable more lift and thrust generation in comparison with others.

The shape of bird wing tip minimizes drag during the up and down strokes of the wing and strengthens the vortex. Thus, these actuation mechanisms and shapes are both important to successfully mimic a bird wing. Moreover, EAPs have also been utilized in actuators for the trailing edges of a fixed-wing UAV to increase the lift. A small lighter-than-air vehicle having EAP actuators whose rudders and elevators have improved the manoeuvrability of EAP blimp.

Researchers have integrated lightweight and mechanically flexible printed transistors and actuators with a paper glider prototype to demonstrate electrically controlled glide path modification in a lightweight, disposable UAV system (Grau et al., 2016). It was concluded that by employing a printing-based fabrication process on a paper glider, it offers an attractive path to the realization of inexpensive UAVs for ubiquitous sensing and monitoring flight applications (Grau et al., 2016).

Similarly, a number of EAPs were employed to mitigate a laminar separation bubble (LSB) in NACA 009 aerofoil (DeMauro et al., 2015). The chord-based Reynolds number and the angle of attack have tremendously affected the size and shape of the LSB. Due to the distribution of the displacement thickness, two things can be noticed: (1) the EAPs triggered early transition of the separated mixing layer and (2) the EAPs decreased the thickness profile, which implies the control of the LSB.

Furthermore, the research programme of electroactive morphing for micro air vehicles (EMMAV) was created as part of the French foundation of Sciences and Technology effort to develop MAVs and nano-air vehicles. The EMMAV's goal was to optimize the performance of MAVs in realistic environments via electroactive morphing (Scheller et al., 2011).

A higher frequent actuation was needed to control and influence the aero-elastic coupling effect induced by both noise and drag (Chinaud et al., 2013). Hence, an actuation mechanism based on piezoelectric stack actuators was developed as a second pillar of the EMMAV research programme. These actuators can achieve a very high frequency of actuation which can be useful to produce trailing-edge vortices breakdown with limited deformation (Scheller et al., 2011).

MIT developed the X-Frame and double X-Frame actuators that amplify the deformation via a scissor-like mechanism. These actuators were applied in Boeing's SMART active flap (Scheller et al., 2015). An amplified stack actuator was optimized by European Aeronautic Defence and Space Company (EADS) in order to be used for the active control of a helicopter rotor (Janker et al., 2006). Finally, a diamond-type amplification mechanism optimized for low-weight and high-energy density (Scheller et al., 2015), yet only allowing for unidirectional amplification.

The potential ink-jet printing of EAPs is a low-cost fabrication technique that would offer accuracy and reliability as well as the availability to distribute them over a wide surface, a further advantage that led to the choice of their use (Aschwanden and Stemmer, 2007; Kudva, 2004). In addition, the design of an actively conformable rotor airfoil that can change its shape (thickness and camber) as it traverses around the azimuth is being supported by the National Rotorcraft Technology Center (Bar-Cohen et al., 1999; Janker et al., 2006; Scheller et al., 2011, 2015; Wierach et al., 2013, 2015).

On the other hand, the research of the optimal design of tendon-actuated morphing aircraft structures has been supported by Defense Advanced Research Projects Agency (DARPA) (Kudva, 2004; Vasista et al., 2012; Zhang et al., 2014). Applications such as the ailerons of the edge flight, rotor blades, wind turbine blades and 'bumps' in the transonic flow (cruise phase of flight of civil aircraft) are developed employing EAPs (Villa et al., 2016). In addition, various European programmes, Tfast ('Transition Rental effects in shock-wave induced separation, EU programme–Level 1) SARISTU (Smart Intelligent Aircraft Structures', EU programme–Level 2) ongoing ranging from TRL1 and TRL3, respectively, relate to EAP.

Also, drones equipped with biomimetic systems may be considered in future projects with imitating bird concepts such as Albatross, which uses velocity gradients near the surface of the sea to effortlessly manoeuvre and travel long distances. These concepts can be studied to actuate the electroactive feathers of the trailing edge (Motta et al., 2016; Scheller, 2015).

While some promising results were shown by recent developments concerning fully self-sensing i-EAP actuators, several challenges are still over there (Bar-Cohen, 2001a). For example, although that there is a comprehensive theory of self-awareness based on the electrochemical nature of CPAs which has been devised and experimentally validated, but it still suffer the lack of success when implemented for controlling these actuators.

In order to develop a better understanding of the material behaviour, advances are needed. Efficient control algorithms and sensors are required to address the challenging requirements for practical EAP actuators. Despite these limitations, EAPs are still attractive because of their unique features that could be fit for sensing, niche actuation and biomimetic applications.

Conclusion

It is now apparent that EAPs belong to a class of active materials that can be used to obtain novel actuator designs and is one of the dominant research topics in smart material applications when compared to other materials in enhancing the actuation proficiency in various systems. They are playing an increasingly significant role in developing the aerospace field. We have enumerated a number of research findings which have substantiated the potential applications of EAPs in aerospace, specifically aircraft morphing. These new advancements are stimulated by the distinct properties, functionality and the accuracy of EAPs. Therefore, the applications of these smart materials as effective actuators can be investigated more effectively by investigating their materials, molecular interactions, electromechanics and actuation mechanisms.

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ORCID iD

Parvathy Rajendran https://orcid.org/0000-0002-7430-1389

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