Electro-Active Polymers
For actuation and sensing in space applications

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Electro Active Polymers (EAPs) respond to an applied electrical potential with displacement. This permits their use for electrically-driven actuation mechanisms and in reverse as strain sensors. EAPs are currently the most promising class of materials for 'artificial muscles', as they are light-weight with high compliance, have high active strains and/or stresses depending on the kind of material (sometimes in excess of natural muscles), fast response (electronic type EAPs only), good controllability and low cost. This paper focuses on the potential of EAPs to provide solutions to integrating actuation and sensing functions required by future space systems. Performance indicators are covered, covering force levels, density, stiffness, displacement, power, and dynamic response. Their limitations are discussed in the context of environmental aspects, such as temperature, pressure, radiation, gravity, and in relation to robustness (degradation, fatigue). Dielectric elastomers are concluded to be the most promising class of EAP for application in a wide variety of space actuation tasks, and some of the possible applications of EAPs in space are investigated. The paper concludes with a short case study on the use of a novel EAP device for a jumping mechanism in a Martian tumbleweed rover is presented as a novel example application.

1.INTRODUCTION

Space exploration requires medium and long-term development of systems capable of providing the necessary functionality for survival in demanding environments. In particular, unmanned devices, such as *deployable structures* and *robots*, as well as *smart textiles* to enhance, protect and extend the performance of humans are key areas of interest. There is a constant drive to reduce the mass and power consumptions of spacecraft and the devices placed in space, which serve to perform increasingly complex tasks. Several of these key constraints can be met through miniaturisation but significant limitations occur via this route. Consequently novel designs for surface and space travel based upon unique technologies, such as new types of actuators, are required. Current actuation technologies are based either on high modulus – low strain materials, such as piezoceramics and magnetostrictors, or on multi-component systems, such as hydraulic, pneumatic or electromagnetic devices. The former technologies are capable of working at high stresses but low strains, whereas the latter systems are capable of producing large strains or displacements but at comparatively low stresses.

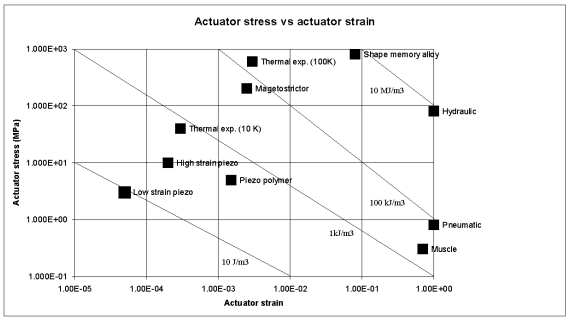

Fig. 1: Actuation stress versus actuation strain for various actuators. The sloping lines from left to right give an indication of the energy storage capacity per unit volume of the various actuators (Adapted from (1)).

Considerable attention has also been directed at shape memory alloys (SMAs) that can deliver both high forces and large displacements. However, the response times and longevity of these materials has yet to be optimised to afford reliable actuator technologies. It is clear from a recent analysis of the performance indices of mechanical actuators[1] that there is a gap between the high stress-low strain and the low-stress – high strain groups. This is the region where most current EAPs systems operate (Fig. 1).

Polymers which can change shape in response to an electric field have been known for over a hundred years but it is only in the last decade that

electroactive polymers have been developed which can be stimulated to produce a substantial change in size or shape. The large displacements have encouraged new thinking in terms of both applications and designs. The natural ease of preparing and shaping such materials, coupled with their low mass and large displacements, opens up new approaches in many traditional areas as well as the potential to enable new technologies. Additionally, the EAP itself may be able to provide a sensing mechanism. In summary, the advantages of EAP-based actuation or sensing are several: Low density materials (mass reduction, inertia forces reduction); Limited number of moving parts (reduced complexity, reduced costs, higher reliability); Possibility of increased redundancy with limited additional economic and weight costs; Direct conversion of electrical, chemical or radiation energy into mechanical work.

2. TYPES OF EAP

In principle there are a wide variety of active polymer systems that can be deployed in space applications. We can classify these either in their mode of operation (Table 2) or the type of material (Table 3).

	One Shot	**Reversible** (Low frequency)	**Cyclable** (High Frequency)
Discontinuous	Shape memory polymers	Liquid crystal elastomers	
Continuous		Gels, Conducting Polymers	Dielectric elastomers, piezoelectrics

Table 1: Active polymer systems classified by mode of operation.

Mechanism	***EAP Type***
Mass/ion transport	Conducting polymers, Gels
Polarisation	*Dielectric elastomers, Piezoelectric*
Molecular shape change	Conducting polymers, Liquid crystal polymers
Phase change	*Liquid crystal elastomers, Conducting composites, Shape memory polymers*

Table 2: Active polymer systems classified by type of material.

There follows a short description of these classified by material type.

2.1 Mass/Ion Transport Mechanisms

One of the first viable artificial actuators utilising conducting polymers was reported by Otero *et al.*[2] and this polypyrrole (PPy) system mimicked the action of natural muscle. Since then, numerous electroactive polymers have been investigated with the view of developing efficient actuators for a wide range of applications, ranging from haptic devices to simple toys. All of these systems are reliant upon the use of *electrochemical reactions* to afford mechanical energy. Actuators based upon conducting polymers involve primarily either an electrical input, effecting either a physical change in the mass of the polymer network by electrically driven diffusion of ions into the body of the polymer *or* by changing the charge of the polymer structures such that charge repulsion effects the requisite alteration of the polymers' properties. Three main polymer types are predominant in the field of electroactive polymeric actuators that operate via volume changes: - polypyrroles, polyanilines and polythiophenes. From these three main types, the development of actuators based upon polypyrroles has dominated.

2.2 Gels

Gel actuators are constructed from lightly cross-linked polymer networks that contain solvent. The presence of the solvent within the polymer network gives the gel its physical properties (stiffness, shape etc). Polymer gels are able to swell by the uptake of solvent within the polymer matrix and this process can be affected by electrical means. The gel expansion depends upon the rate of flow of solvent into the gel matrix. There are several mechanisms, which can be used to change the equilibrium swelling extent, for example temperature, chemical, pH, light as well as, electrical. The incorporation of magnetic nanoparticles leads to materials that can be used as magneto-actuators.

2.3 Dielectric elastomers

Dielectric elastomers in their simplest form are elastomeric or rubber materials that are incompressible but highly deformable. An electric field is applied normal to the sheet thickness through two compliant electrodes. The force developed between the electrodes compresses the elastomer in the direction parallel to the electric field. As the rubber is incompressible (with a Poisson's ratio of about 0.5) the sheet extends in all directions normal to the electric field. The compliant nature of the electrodes means that as the electrodes are also extended they do not develop a stress to oppose the deformation. The resultant stress is often referred to as the Maxwell Stress.

The excellent figures of merit possessed by dielectric elastomers in several respects (high actuation strains and stresses, fast response times, high efficiency, stability, reliability and durability) make them the best performing materials currently available for polymer actuation, and many different configurations for dielectric elastomer actuators already exist (Fig. 2). The price for achieving these high-level capabilities is represented by the high driving electric fields needed (order of 100 V/μm). For a definite polymer thickness, such field levels can be reached by using high voltages, which may be disadvantageous in many applications. For this reason, in order to reduce the driving electric fields, polymers with high dielectric constant are necessary.

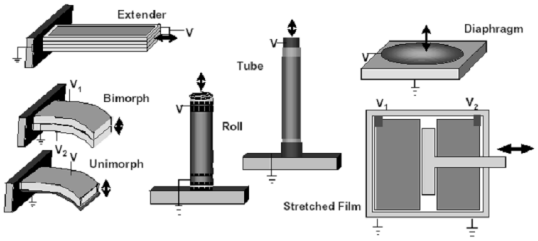

Fig. 2: Existing configurations for dielectric elastomer actuators.

2.4 Piezoelectric Polymers

The piezoelectric effect is an essential property of many non-centrosymmetric materials including synthetic polymers, biological systems and ceramics. Traditionally commercial and scientific interest has focused on polyvinylidenefluoride (PVDF) that is a semi-crystalline polymer. However, in recent years, interest has broadened to amorphous and liquid crystalline materials. The basic mechanism requires a coupling between the polar order of a material and the shape. The polar order may be the equilibrium configurations of crystals and liquid crystals or it may be imposed by electric poling as in the case of amorphous polymers. Imposition of an electric field causes these polar ordered regions to align themselves with the field resulting in changes to the sample dimensions. Conversely deforming the sample leads to changes in the alignment of the polar regions, which in turn leads to the development of an electric field.

2.5 Molecular Shape Change

In essence we can think of all active systems as controlling the shape of the polymer conformation and coupling that change to the macroscopic sample dimensions. Many systems including biological have been identified which undergo shape changes upon a variation in an environmental factor such as chemical, temperature or ionic strength. Indeed, controlling molecular shape changes is the very basis of living systems. The simplest and oldest synthetic actuators are based on chemically activated conformational transitions. However, relatively few of such mechanisms provide a route to electrically active polymers without recourse to complex control systems. The thiophene based molecular actuator developed by Madden *et. al.*[3], is an example of an ionically driven system that of course can be activated electrically.

2.6 Liquid Crystal Elastomers

Liquid crystal elastomers are essentially polymer networks that exhibit liquid crystal phases. The liquid crystal state is characterised by the presence of long-range orientational order. Polymer networks are largely driven by entropy and the molecular spans in a network adopt random coil configurations. Mixing liquid crystalline forming molecules with a network would normally lead to phase separation but this can be inhibited by chemically joining the liquid crystal forming units, often referred to as mesogens, to the polymer chains.

The presence of the liquid crystal forming units in a liquid crystal phase leads in most cases to an ordered polymer conformation. If the material is heated to the isotropic phase, that order is lost and the chain adopts an isotropic random walk configuration. The change in molecular shape can be coupled to the macroscopic sample by cross-linking to form a network. The dimension change, which can be achieved, is simply related to the extent of ordering in the liquid crystal phase and the state of order present when the system was cross-linked. The mechanism is invoked by changing the phase of the material. This can be achieved using electrical heating with conduction pathways embedded in to the material or by destabilising the liquid crystal phase using light sensitive molecules.

2.7 Shape Memory Polymers

Shape memory polymers exploit the fact that the configuration at the point of cross-linking in a polymer network is the lowest energy configuration. Any deformation away from that configuration increases the energy. In a network with crystallisable units, the effective network points may be the crystals, which have formed with several chains passing through each crystal or the original network points. Thus, stretching the rubber at a temperature above the crystallisation point and then cooling it in that extended shape will lock-in the deformation. On heating to melt the crystals, the original network configuration is recovered.

Table 3, below, summarises the stress, strain and specific energy storage of the various groups of EAPs discussed above. For comparison, the performance of piezoceramics and shape memory alloys has also

been included. The values reported are ranges of values obtained from published material.

Material	**Strain Range** (%)	**Stress Range** (MPa)	**Specific Energy Storage Capacity** (MJ/m^3)
Conductive Polymers	6 - 70	0.1 – 6.5	0.08 - 45
Piezoelectric polymers	10 - 45	0.4 – 4.5	0.2 – 2.0
Liquid crystal polymers	2 - 40	0.3 - 5	0.1 – 2.0
Shape memory polymers	100 - 200	0.5 - 2	1.0 – 4.0
Dielectric elastomers	15 - 100	0.02 - 6	0.075 – 25
Active polymer gels	5 - 30	0.00015 – 0.2	0.00005 – 0.06
Piezoceramics	0.1 – 0.3	10 - 40	0.03 – 0.12
Shape memory alloys	7 – 8.5	500 - 700	35 - 60

Table 3: Comparison of EAP performance for actuation.

3. EAPS AND THE SPACE ENVIRONMENT

Space presents a challenging environment with many extremes of temperature, pressure, radiation and energetic particles. As well as the limitations imposed by the space environment (high and low temperatures in particular) the lengths of missions will require extended lifetimes of the materials used with minimum degradation. The two main environments are (i) within an enclosure with control of one or more of temperature, pressure, gravity and radiation and (ii) unenclosed with variable environmental conditions with additional factors such as radiation and particulate fluxes. Unenclosed temperatures vary from 4K in general space to between 80K and 390K on the surface of Mars or the Moon. The lower end of this temperature range lies outside the conventional operating range of polymeric material systems. Table 4 summarises the ability of the various EAPs to function in the space environment.

Temp/ Celsius	Dielectric Elastomers	Polymer Gels	Conductive Polymers	LC Elastom.	Piezoelectric Polymers	Shape Memory Polymers
Moon shade--150	Y	N	N	N	N	Yt
Moon sun-+140	Y	N	N	N	N	Yt
Moon mean--25	Y	Y(?)*	Y*	N	N	Y
Mars shade--143	Y	N	N	N	N	Y
Mars sun-+30	Y	Y	Y	Y	Y	Y
Mars mean-+60	Y	N	Y(?)	N	N	Yt
Deep space hade- -270	Y(?)	N	N	N	N	Y
Deep space sun-+125	Y	N	N	N	N	Yet

Table 4: The ability of the various EAP types to function in the space environment (*-using non-aqueous solvents, t-with shielding).

Depending on the type of EAP material, either low temperatures (below their glass transition or below the freezing point of the solvent) are critical, or high temperatures leading to unacceptable softening or melting and degradation of the materials. The temperatures experienced when EAP actuators are exposed to solar radiation can be controlled using suitable shielding.

Space is essentially a high vacuum while the surface of the Moon and of Mars exhibit much reduced pressures (~mb) compared to the surface of the Earth (1000 mb). Clearly a high vacuum is not compatible with un-encapsulated systems containing fluids and other low molecular weight components. The varying gravitational field has limited impact at a materials level, although it may be an important factor if material preparation or material actions such as self-repair are performed in space. Materials in space will be exposed to energetic charged particles in the MeV range both in interplanetary space and in the magnetospheres of planets, especially of the earth. It is difficult to shield critical components from such particles especially in view of the penalty incurred in additional system mass. Such energetic particles will lead to highly localised ionisation, charging and displacement damage. In space, polymeric materials degrade because of high fluxes of atomic oxygen, bombardment by low and high-energy charged particles, the full spectrum of solar radiation. Polymers have been widely used to record ionisation events[4,5,6] and so significant damage is possible. It is usually the case that many processes are taking place

concurrently due to both the range of energies but also the range of possible reactions within the polymer. The complications are often compounded by the presence of impurities or additives. These can have an overriding effect, both beneficial and deleterious. The interaction of radiation with organic material is usually very localised in that it affects directly specific chemical bonds. Both chain scission and cross-linking are common in polymer systems and embrittlement is a common failure mechanism. For many actuator systems additional cross-linking will severely affect or eliminate the actuator response. Aromatic polymers are usually more resistant to cross-linking and high-energy radiation; PEEK and Polyimides are two examples. However, the extended conjugation may make them more susceptible to UV exposure, which is a major problem both on Mars and in space. Some UV resistance can be built in using selected absorbers within the polymeric material as is widely used in earth-based building materials and other polymers for external use. However, the UV spectrum is considerably extended on Mars and new stabilisers may be required. Some of these additives may not be applicable in situations where electric fields are applied due to the enhanced conductivity from the additives. Typical glassy polymers have general high-energy radiation tolerances of 10^6 Gray. The impact of radiation on engineering polymers has been widely studied and polymers, which exhibit an enhanced tolerance to radiation, have been identified. *However, for many active polymer material systems little is known about the radiation resistance properties.* Unenclosed systems will be exposed to low energy ions ~ 1-4keV in the solar wind and to particulates both in terms of interplanetary meteoroids and debris as well as planetary dust. For example, the lunar surface contains ~ 50% of particles smaller than 50μm, while on the surface Mars there is a significant probability of dust storms. Such dust will adhere strongly to surfaces and may limit optical transmission as well as interfering with mechanical performance. All materials will receive electromagnetic radiation in the form of the solar flux and here the radiation in the UV range is of particular importance, as it will in general lead to degradation of the polymers at the molecular level. This is a reasonably well-understood area, although there have limited studies on the impact of UV radiation of active polymer systems, except in the cases where the polymer is light activated. The absence on Mars of an UV absorbing atmosphere as in the case of the Earth leads to an enhanced intensity of light in this region of the spectrum. However, the high dust level mitigates against this higher level and it is estimated that the integrated UV flux in the region 200-400 nm is similar to the Earth's. However, the shorter wavelength ranges UVC (200-280 nm) and UVB (280-315 nm) contribute more and are particularly damaging to synthetic organic matter as well as biological materials.

In general the construction and deployment in to space of instrumentation or exploration devices has a long cycle time. Clearly the shelf life of the materials used is of particular importance. If the construction takes place on earth, the material environment is ~ 22C and a relative humidity of ~ 55%RH. In some cases a more controlled environment probably at lower temperatures will be required. Although the temperature range appears to be the most limiting factor, degradation to prolonged exposure to radiation inherent in space travel and deployment may be the key factor to overcome.

4. EAPS IN SPECIFIC SPACE APPLICATIONS

4.1 Smart textiles

Smart Textiles with added functionality over and above the conventional protective purpose would be useful for application both within the pressurised environment of a space station or habitat, and also for incorporation into EVA suits. In practice, smart textiles may be classified depending upon their functionality and adaptation to the changing situation:

(i) Passive Smart: Providing additional features in a passive mode i.e. irrespective of the change in the environment e.g., a highly insulating coat which remains insulating to the same degree irrespective of the outside temperature. (ii) Active Smart: Tuning functionality to specific agent or environment e.g., a breathable fabric would allow perspiration to pass but would not allow rain droplets to enter the fabric, variable insulation[7]. In this category one should include: a) fabrics which incorporate "fibrous actuation elements" base on EAPs to provide external muscle-type functions to complement biological muscles; b) plant "stomata" type bending structures, also based on EAPs, capable of providing selective and adaptive mass and heat transfer. (iii) Intelligent: Adapting their functionality to changing environment but requiring some form of "intelligence" for the actuation control in order to provide high levels of protection even in extreme environment conditions and changes. Sensing fibrous EAPs, integrated in fabrics for physiological and health monitoring, for example, will also require additional software and hardware for implementation.

However, a real actuation function is only achieved in types (ii) and (iii). In this case, the electronic behaviour of the fabrics as a whole needs to be studied as a complex electronic network since their properties will be determined by the functional integration of electronics and EAPs in the yarns and by their topology in the fabric. Moreover, the need

of maintaining the mechanical flexibility of textiles reduces the choice of possible materials and technologies suitable for the production of smart textiles: electrical conductivity and its modulation cannot be obtained through traditional semiconductors[8].

The development of textile yarns with electronic functions is usually obtained using conjugated polymers (essentially organic semi-conductors), such as polyaniline, polypyrrole and polythiophene. The conductivity in these polymers is due to the ease of electronic jumps between chains, owed to the presence of dopant agents, able to modify the electron amount in the bands. The main advantages of using conductive polymers are the low actuation voltages, and their ease of integration into textile fabrics, provided the material used has mechanical properties not differing too much from those of textile substrates[9]. After a suitable material selection, the goal of obtaining a smart appears to be achievable in two ways:

(i) Electronic/electrical functionalised fabrics are obtained by depositing the selected materials on it, according to a predetermined geometry (sensing fabrics: Lycra/polypyrrole);

(ii) Fabric is obtained starting from functionalised fibres such as those made of actuating polyaniline fibres[10].

The typical approach to both the above strategies is to achieve the optimisation of conducting polymer technology; this represents a possible route to create an actuator having muscle-like performance. Such an optimisation can be reached by modifying the electrolyte, the electrode geometry or the material microstructure. An alternative approach consists of designing the artificial muscle from the molecular level up, where force and displacement generation comes from chemically engineered molecule building blocks changing shape upon application of an electrical stimulus[11].

The response time of these actuators, as in all diffusion-controlled processes, appears to be dependent on their geometry; the development of actuating fibres of diameter as small as possible is a key factor in their effective utilization[12]. Developments of polymer preparation to obtain a fibrous geometry are also reported by the same authors[12].

EAPs have been incorporated into the design of the 'Chameleon' next generation spacesuit concept[13].

4.2 Robotics

The use of EAPs in robotics is often seen as a means of replacing more conventional electro-mechanical, pneumatic and piezoceramic based systems with "muscle-type" analogues. There are however important differences, as well as similarities, between biological muscles and EAPs, which need to be considered in relation to robotic applications for space exploration. One of the most important differences is that muscles (and their integrated system of tendons) are *fibrous structures* and relatively few EAPs are available in fibrous form. The advantages of fibrous polymer structures (biological or artificial) for actuation are considerable:

- Directionality of force or displacement
- Possibility of arranging sub-units in parallel/series combinations to tailor force/displacement characteristics
- Redundancy because of multiple load paths
- Small size possible for individual elements (important for easy integration within textile and robotic structures)
- Wide range of two- and tri-dimensional architectures possible to "diffuse" and optimise force transmission in different directions, combined with the advantage of using current textile technologies for fabrication
- Advantages of small "active" fibres in relation to response times for those systems which rely on mass transport for actuation (reduction of diffusion path lengths = increase in speed of response – this is indeed the same principle used in real muscles)
- Owing to nervous control and its particular structure, it can function as a variable stiffness system, providing a wide range of "effective" compliances.

Electro active polymers appear to provide the best mechanism for replicating the properties of animal muscles and it is clear that a successful artificial muscle will need to replicate both the small scales of the muscle sarcomeres that can achieve fast response. With their packing into fascicules - and hence into fibres - that can transmit significant forces and powers into tendons and bones. There have been many other contenders for a muscle-like actuator and the pneumatic system known as McKibben Muscle is probably the closes current technology can come to the performance of natural muscles in terms of power and energy densities. There are several problems with McKibben Muscles quite apart from their consideration for space applications. These include the noise and weight of valves, the difficulty in achieving accurate control and the weight of the power source.

One interesting observation on McKibben muscle structures is the work by Vincent and Jeronimidis[14] who filled the space within a McKibben like structure with a gel and demonstrated this as a possible mechanism for actuation. Although reasonable forces and strains were available from this actuator design the response time was slow primarily because of diffusion limitations of the bulk

gel used. Current EAP technology still has several challenges before the abilities of animal muscle can be demonstrated - these include:

- Increasing the *max recoverable strain*. EAPs currently achieve strains in the order of 2-10% over the operation cycle, muscles can achieve strains of 10-25%
- *Response times*: It has proved difficult to get fast response times from EAPs and 0.1 Hz is considered a typical response for a poly pyrrole actuator with dimensions of 30mmx10mmx0.1mm. Muscle response times are higher up to 5 muscle length/second and a humans joint may have a frequency response of up to 10 Hz
- Muscles also have inbuilt mechanisms for *self repair* in response to damage
- The animal system has both a complex system of *joint-state sensing* via muscle spindle sensors, tendon force sensors, and a range of cutaneous touch sensors. The brain however is able to ignore most of this information via strong internal models, unless there is a need to heed information that is at variance with the brains internal model.

Thus, although there is an attraction in simply trying to replicate muscle response via an electro-active polymer there are greater gains if the actuator can be considered in the context of the mechanical, sensing and control structures around it.

4.2.1 Current applications of EAPs in space robotics

There are not many examples of EAP usage in robotics, most researchers preferring to design systems with more established technologies. There are two proposed space applications. The first of these is the windscreen wiper proposed for the MUSES-CN[15]. The wiper is made from an IPMC with an input voltage signal of about 0.3 Hz. This results in movement of the dust wiper of about 90 degrees.

The second proposed space application is for a robotic grasper to collect samples[16, 17]. This again is made from IPMC and consists of a four-finger grasp hand on the end of a single link robot. The response time for this actuator is over several hours but the gripper appears to operate at low temperatures and is able to grasp and lift a load of 10g.

4.2.2 Haptics and Telerobotics

Electro active polymers and novel actuators are being considered in the design of haptic interfaces and as a method of providing feedback to the operator of telerobotic systems. Most work in haptics has looked at the properties of materials such as electro and magneto-rheological fluids (MRFs), and although not an EAP technology this does serve to indicate the potential and limitations. Early work on producing tactile surfaces used EAPs beneath a protective skin with regions that could be 'activated' thus giving a differing sense of the haptic interfaces surface. More recent work has used MRFs to allow a person to 'sculpt' shapes along magnetic field lines. The practicalities of this idea are somewhat limited since the person interacts directly with the fluid and usually wears surgical gloves so as to avoid the mess once the hand is withdrawn from the interface.

4.3 Deployment

EAPs are well suited as actuators for deployment applications such as solar panels or antennae because there is generally no need for "fast" actuation. Also, deployment is often one-way only, and this is an advantage in view of the problems associated with the very limited reversibility of many EAP shape change mechanisms and their relatively high performance deterioration as a function of cycling (excluding perhaps dielectric elastomers). There are two main strategies for deployment actuation which can be considered: stimulating the EAP system at the moment of deployment – direct actuation (applying voltages or exposing gels to solvents) or using the EAPs to provide work to store energy in an intermediate spring system device which can then be released – indirect actuation. Unfolding of leaves has stimulated some research into deployment driven by turgor pressure mechanisms in plant cells[18]. The interesting aspect of these studies is the concept of a system of *distributed actuators* of small size which, acting cooperatively, provide the effect. The advantage of this approach for direct actuation is that, in small size distributed systems, it may be easier to provide the stimuli and to limit some of the problems of large volume EAPs (mainly solvent diffusion rates or high voltages). It is interesting to note that the deployment of insect wings when the animal emerges from the pupa stage is also provided by fluid pressure into a series of distributed flexible channels, which can then be stiffened after the deployment is completed[19]. This type of diffused actuation with EAPs can best be achieved if, as mentioned at various points in this report, the technology for obtaining EAP actuators in "fibre" form can be developed.

5. TEST CASE – MARS BALL ROVER

Having briefly discussed some of the possible applications of EAPs to space systems, in this section we turn to a specific study currently being performed by the ACT at ESTEC into a Martian tumbleweed rover, and specifically to the problem of incorporating a jumping mechanism to enable this rover to move over obstacles.

Dielectric elastomers are viewed as the most promising class of material for many actuation tasks, owing to their high active strains, stresses, response times, stability, durability and reliability. As presented above (Fig. 2), so far several configurations for dielectric elastomer actuators have been proposed, demonstrated and studied. Owing to their linear (along a line) actuation capabilities, tube and, mainly, roll actuators are potential candidates for the realisation of "*artificial muscles*". However, they present a mechanism of actuation opposite to that of natural muscles: under electrical stimulation they elongate, instead of contract. In order to overcome this limitation, actuators able to undergo electrically activated contractions are demanded. On this regard, the Research Centre "E. Piaggio" has recently developed a new actuating configuration (Fig. 3).

Fig. 3: Photograph of a prototype of the new kind of actuator.

The new configuration is based on a structure designed more generally for EAP devices and recently patented and presented[20,21,22]. It consists of a hollow cylinder of dielectric elastomer, having two helical compliant electrodes integrated within its wall, in a parallel spring arrangement. By applying a voltage difference between the electrodes, the interactions among their free charges cause axial contractions of the actuator, as well as related radial expansion.

Therefore, devices based on this actuation scheme may be regarded as electrically activated polymer springs. By assuming that the elastomer is a linearly elastic body and that the applied electric field E is approximately uniformly distributed inside it, it can be demonstrated that the following relation describes the axial strain generated in this configuration:

$$Axial\ \ Strain = \frac{\varepsilon_0 \varepsilon_r E^2}{Y}(\cos\alpha - sen\alpha) \qquad (1)$$

Where ε_0 is the dielectric permittivity of vacuum, ε_r is the relative dielectric constant of the material; Y is its elastic modulus and α is the angle of inclination of each electrode with respect to the device axis. Fig. 4 shows results of a preliminary characterisation of the linear electromechanical contraction performances of the first prototypes. In particular, this figure reports axial contraction strains obtained in response to the application of the indicated electric fields.

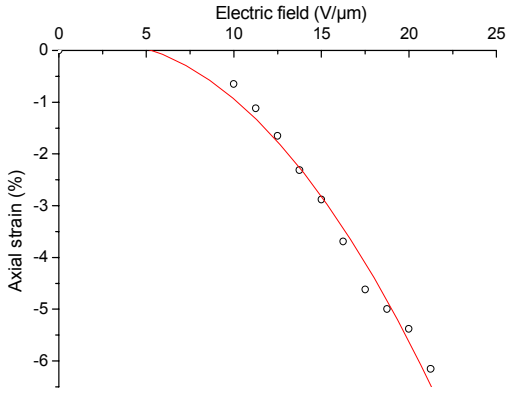

Fig. 4: Preliminary data on axial contraction strain versus applied electric field (data from the Research Centre "E. Piaggio").

These results indicate that, presently, contraction strains of about –6% at 22 V/μm are achievable. However, higher performances are expected with future developments of the fabrication process, currently under development at the Research Centre "E. Piaggio". For instance, in our opinion strains of the order of –10% at about 25-30 V/μm can be considered as a realistic near target, so that they have been assumed as a reference for the analysis developed in this study.

The actuator is integrated in the host structure represented by the spherical shell, assumed for the analysis to have a radius of 1m and a thickness of 1mm. The contracting dielectric elastomer actuator is placed along the sphere diameter. In principle, the application of a definite electric field to the actuator will tend to compress it, causing a deformation of the shell and, lowering the position of the centre of gravity (CoG) of the system. The following release of the actuator will trigger the jumping of the sphere, by turning the stored strain energy into kinetic, and ultimately gravitational energy. Numerical simulations have been performed, according to the following simplifying assumptions:

- No coupling has been implemented between the electrical and mechanical domains, so that deformation does not affect the electrical behaviour.
- The system has been assumed as linear with respect to its constitutive relations. Moreover, materials used for both the shell and the actuator is assumed as homogeneous and isotropic.
- The mechanical environment of the system under study has been assumed to consist only of the Mars' gravity

and the reaction of the floor, modelled as a unilateral constraint (the sphere can loose contact with the floor). A contact algorithm has been implemented as described in (23).

The assumed initial conditions: the sphere is dropped from a height of 1 mm, starting with a null velocity. The parameters of the shell and of the actuator assumed for the simulations: see Table 5.

In order to investigate the effects of the stiffness of the sphere material on the resulting performances, the different values of Young's modulus (elastic modulus) reported in Table 5 have been assumed for the numerical simulations. These values have been selected in consideration of the reasonably different stiffness required for the sphere.

Shell	Young's modulus	10 MPa, 100 MPa
	Poisson's ratio	0.3
	Density	500 kg/m^3
	Dimensions	Radius: 1 m Thickness: 0.001 m
	Mass	6.3 kg
Actuator	Young's modulus	100 kPa
	Poisson's ratio	0.49
	Density	1000 kg/m^3
	Dimensions	R1= 0.05 m R2=0.005 m Length: 2 m
	Mass	15.6 kg
	Active strain (free stroke)	-10%
	Stimulation time	0.2 s

Table 5: Assumed parameters for the simulation.

The commercial FEM code ADINA has been used for the simulations, since its features comply with the requirements of the analysis. A transient dynamics simulation has been performed: the shell has been discretized by means of 9-nodes MITC shell elements, while the actuator has been represented by 2-nodes beam elements.

The simulation of the actuation mechanism has been implemented by means of a thermal analogy: in correspondence to the maximum active strain that the actuator is able to provide, a fictitious negative coefficient of thermal expansion has been assigned to the actuator material (silicone), so that, once a unit variation of temperature is applied to it, its contraction matches the required maximum active strain, assumed as –10%. In terms of effective electrical stimulation, this strain corresponds to the application of an electric field of about 25-30 V/µm. The active stimulation of the actuator has been simulated with the application of step stimuli having a length of 0.2s and a magnitude corresponding to the imposed strain of –10%. Fig. 5 presents the jumping sphere actuated.

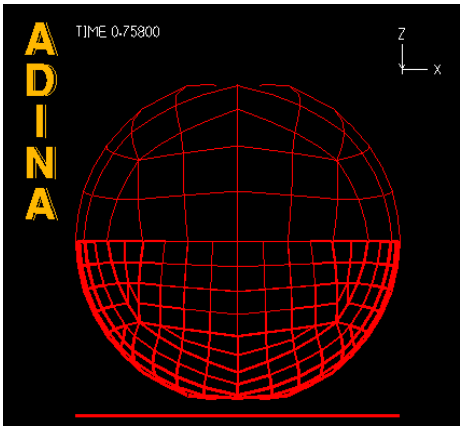

Fig. 5: The actuated sphere.

The plots reported in Figs. 6 and 7 show, for the two considered elastic moduli of the sphere, the time dependence of the vertical (z) displacements of the (geometrical) centre and bottom points of the sphere, with respect to their initial positions.

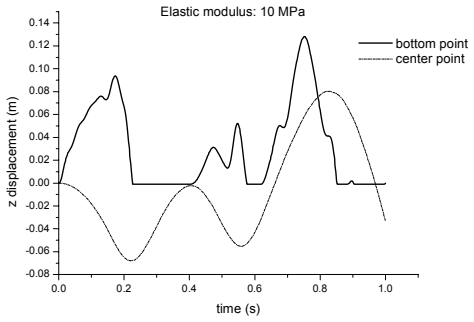

Fig. 6: Time dependence of the displacements of the centre and bottom points of the sphere (having an assumed elastic modulus of 10 MPa).

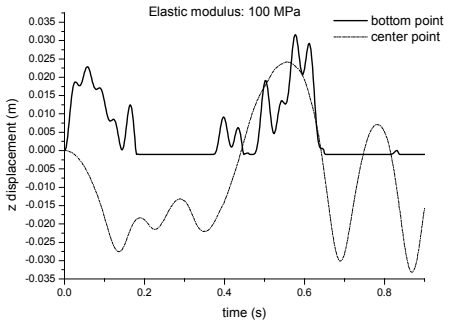

Fig. 7: Time dependence of the displacements of the centre and bottom points of the sphere (having an assumed elastic modulus of 100 MPa).

Elastic modulus of the sphere (MPa)	**Displacement of the center point of the sphere (cm)**	**Ratio between displacement and rest diameter of the sphere**
10	8	4%

100	2.5	1.3%

Table 6: Maximum displacement of the centre point of the sphere for the two elastic moduli.

Therefore, in this case the most significant variable quantifying the jumping capability of the system is represented by the displacement of the geometrical centre point of the sphere. On this regard, the maximum achievable displacement of this point is listed in Table 6.

5.1 Discussion

In this configuration, the higher the compliance of the sphere, the lower the constraining action on the actuator, which, therefore, can be easily electrically strained, leading to the elastic energy accumulation. As a result, the sphere will be pushed by the actuator towards the floor and, when the actuation force is released, it will jump, converting strain energy into gravitational energy. This is confirmed by the simulation results presented in Figs. 6 and 7, which indicate that the jumping capability of the sphere increases with the compliance of the sphere.

However, with a relatively compliant sphere, the actuator strains it mainly in the two zones located around the points of its connection to the sphere. Furthermore, this phenomenon is emphasized by the compliance of the shell. Therefore, the effective jumping performances enabled by this configuration are identified by the achievable displacement of the centre of the sphere, rather than that of its bottom point. Fig. 7 reveals a maximum displacement of the centre of 8 cm, corresponding to the 4% of the rest diameter of the sphere, despite a maximum displacement of the bottom point of 13 cm, representing the 6.5% of the rest diameter of the sphere.

On this regard, it is interesting to note in Fig. 7, for instance, that during the 0.2s-long active contraction phase of the actuator, the bottom point is lifted, while the centre point falls down. At the end of this phase, the sphere is compressed (mostly at its top and bottom points) and when the actuator is released, the center of the sphere starts to be lifted, while the bottom point does not move until the sphere completely recovers its original shape, giving rise to the following evolutions of the bottom and center points described by Fig. 7.

A possible way to increase the performance of this configuration would be to adopt a variable thickness for the sphere's skin, with a higher thickness close to the actuator's hinges, so that the local strain effect would be lower.

The simplified nature of the performed analysis suggests, in reason of these interesting results, to consider a jumping height of the order of 8cm as a first-approximation estimate of the effective jumping capabilities of such a kind of system. Owing to the theoretical scale-invariance of the performances of dielectric elastomer actuators and to the linearity of the constitutive relations assumed in the simulations, these results can be reasonably assumed as linearly scalable for a system having dimensions one order of magnitude higher. Thus for the current Tumbleweed rover design being studied at ESTEC (a diameter of 10m), a jumping capability of somewhere around 0.4m is likely, a very useful mechanism for extracting the rover (which would be wind propelled) from situations in which its motion is constrained by an obstacle.

6. CONCLUSIONS

A review has been given of the types of EAP currently being investigated for use as actuators and sensors, and a discussion of the likely problems and issues surrounding their use in space applications. The currently most favored type of EAP for actuation is the dielectric elastomer, which is favored by high active strains, stresses, response times, stability, durability and reliability. A simulation of the use of this EAP in a novel type of spring actuator for a Mars tumbleweed rover has been described as an example case.

REFERENCES

1. Huber J. E., Fleck N. A., Ashby M. F. (1997). The selection of mechanical actuators based on performance indices. Proceedings Royal Society London A- Mathematical Physical and Engineering Sciences 453: 2185-2205.
2. Otero T.F., Angulo E, Rodriguez J, Santamaria C (1992). Spanish Patent, E.P. 9200095, 1992.
3. Madden J.D., Peter G., Hunter I.W. (2002). Conducting Polymer Actuators as Engineering Materials. In SPIE 9th Annual Symposium on Electroactive Materials and Strucures. 4595:424-434.
4. Ivanov V.S. (1992). Radiation Chemistry of Polymers. VSP.
5. Clegg D.W. and Collyer A.A. (1991). Irradiation Effects on Polymers. Kluwer.
6. Holmes-Siedle A. and Adams L. (2002). Handbook of Radiation Effects. OUP.
7. Dawson C., Vincent J.F.V., Jeronimidis G., Rice G. and Forshaw P. (1999). Heat transfer through penguin feathers. J. Theor. Biol., 199:291-295.
8. Gregory R.V., Kimbrell W.C., Kuhn H.H. (1991). Electrically conductive textile composites. Journal of Coated Fabrics 20:1-9.
9. Rocchia W., Mazzoldi A., Vozzi G., De Rossi D. (2003). Exploiting conducting polymer fiber radial expansion for bioinspired actuation, EAPAD-SPIE San Diego 2003:102.

10. Mazzoldi A., De Rossi D., (2000). Active polyaniline fibres for steerable catheter, Electroactive Polymer Actuators and devices (EAPAD) (ss 3987), Part of 7th Annual International Symposium on Smart Structures and Materials, Newport Beach, CA, USA:273-280.
11. Madden J.D., Madden P.G. and Hunter I.W., (2001). Polypyrrole Actuators: Modeling and Performance. In Electroactive Polymer Actuator and Devices Conference, SPIE 8th Annual International Symposium on Smart Structures and Materials, Newport Beach, CA.
12. Bobbio S.M. et al. (2000). "Scalable Synthetic Muscle Actuator"; Proc. SPIE Conf. On Smart Structures and Materials 3990: 206-218.
13. Hodgson, E. W. (2001). A Chameleon Suit to Liverate Human Exploration of Space Environments. NIAC Final Report.
14. Jeronimidis G. M., (2002). Coupling between active polymer gels and fibre structures for tailored functionality. In ACTUATOR 2002 - 8th International Conference on New Actuators (Ed H Borgmann), Bremen.
15. Bar-Cohen, Y., Leary, S., Yavrouian, A., Oguro, K., Tadokova, S., Harrison, J., Smith, J., Su, J. (1999). Challenges to the Transition of IPMC Artificial Muscle Actuators to Practical Application. MRS Symposium Proceedings.
16. Sahoo H., Pavoor T., Vancheeswaran S. (2001). Research News, Current Science 81(7), Dec.
17. Bar-Cohen Y., Xue T., Shahinpoor M., Simpson J., Smith J., (1998). Flexible, Low mass robotic arm actuated by electroactive polymers and operated equivalently to human arm and hand. In Robotics 98: 3rd Conference and Exposition on Robotics for challenging environments. Albuquerque, New Mexico.
18. Kobayashi H., Kresling B. and Vincent J.F.V. (1998). The geometry of unfolding tree leaves. Proc.Roy.Soc.Lond. B 265:147-154.
19. Wootton R. J. (1981). Support and deformability in insect wings. J. Zool. Lond. 193:447-468.
20. Carpi, F., De Rossi, D. (2004). Theoretical description and fabrication of a new dielectric elastomer actuator showing linear contractions. Proc. of Actuator 2004, Bremen 14-16 June 2004, pp. 344-347.
21. Carpi, F., De Rossi, D., (2004). Electroactive polymer contractible actuator. PCT International Application PCT/IB2004/001868.
22. Carpi, F., De Rossi, D. (2003). Attuatore elettromeccanico contrattile a polimero elettroattivo con elettrodi deformabili elicoidali. Italian Patent PI/2003/A/000043.
23. Bathe, K.J. and Chaudhary, A. (1985). A Solution Method for Planar and Axisymmetric Contact Problems. Int. J. Num. Meth. in Eng., Vol. 21, pp. 65-88.