FINAL REPORT

EAP-BASED ARTIFICIAL MUSCLES AS AN ALTERNATIVE TO SPACE MECHANISMS

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This report covers the work carried out at the University of Reading under contract No 18151/04/NL/MV

The aim of the study is to assess the potential of Electro Active Polymers (EAP) as alternatives to conventional systems in relation to actuation and sensing for space exploration

TABLE OF CONTENTS

1. INTRODUCTION

Space exploration requires medium and long term development of suitable systems capable of providing the necessary levels of functionality for survival in demanding environments. Unmanned devices, such as *deployable structures* and *robots*, as well as *smart textiles* to enhance, protect and extend the performance of humans, have been identified at the meeting with ESTEC/ESA as key areas of interest. This study focuses on the potential of Electro Active Polymers (EAPs) in providing solutions to the scientific and technical problems of implementing and integrating actuation and sensing functions relevant to the selected applications and to the "conceptual demonstrator" suggested by ESTEC [Mars Robotic Jumping Locomotion]. Performance indicators of actuators, biological or artificial, have been included, covering force generation levels, density, stiffness, displacement, power, 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). Sensors performance has been related primarily to mechanical stimuli (pressure - mechanical, sound, or other) as well as sensitivity and conversion of stimulus into signals. Typical response times and reversibility aspects are also included.

2. BIOMIMETIC ASPECTS

Colonisation of earth by life forms of all kinds presented a similar challenge to that faced today by space exploration, i.e. active survival in demanding physical environments (temperatures, radiation, pressures, gravity, etc.….). In biology, three key functions are considered critical for survival: Sensing-Perception-Actuation (The EU has a programme on Life-Perception-Systems within the Future and Emerging Technologies initiative). Evolution is nature's method for designing effective solutions and it is useful to look at existing biological systems for inspiration in relation to applications of EAPs. In the context of this study, two particular functions have been considered: *actuation* and *sensing*.

Although the basic energy source for actuation and sensing in nature is ultimately solar radiation, animals and plants have evolved a variety of specialised mechanisms to convert, store and deliver this energy. The archetypal biological actuator which has stimulated a great deal of research in EAPs is muscle; indeed the literature is full of references to "artificial muscles" based on these systems. However, there are also examples of actuation in plants which, in many respects, are conceptually closer to EAPs than muscles.

2.1 High Performance Muscles

It has long been known that trade-offs exist between contraction velocity and force production in muscles. Pioneering work by A.V. Hill between the 20's and 50's (Hill, 1922, 1938, 1949) first characterised the force production behaviour of muscles. Generally, if high-speed actuation is required, then force production is decreased. As a consequence, organisms have evolved diverse strategies to maximize force, velocity and amplitude of muscular contraction. In this section, we explore a few biological exemplars of possible ways of maximizing the usefulness of actuation systems, that, by a biomimetic approach, could be used as the basis of actuators energised by EAP muscle mimics.

2.1.1 *Energy storage and delivery*

Many organisms are known to employ elastic energy storage as a means of either decreasing the cost of locomotion or to enable actuation to occur at a faster rate than would be possible by muscular contraction alone. Many systems for storing energy, and their underlying mechanical principles, are reviewed by Alexander (1988). Mechanisms predominantly use a proteinaceous material as the compliant spring material. Fleas and locusts store strain energy in blocks of the protein resilin prior to jumping and it is also found in the wing roots of flying insects (it acts to decelerate the wing at the end of the up- and down- strokes and returns energy as the wing direction reverses). Resilin is a highly efficient as it returns over 96% of energy stored in it when deformed by (relatively) slow-acting muscles (see Vincent, 1982). In birds, for example, the primary flight feathers are known to have the capacity to store considerable energy (Pennycuick & Lock, 1976) although subsequently it was found that the furcula, or wishbone, is also an important store of elastic energy (Jenkins *et al*., 1988). Other examples occur in mammals, where perhaps the best-known examples are in marsupials that hop. Biewener & Baudinette (1995) reported that elastic energy recovery in wallabies hopping at 6.3 m s^{-1} was as high as 25% of metabolic energy expenditure.

Precise control of the release of stored energy can result in very fast actuation resulting in exceptional power output. The Mantis shrimp (*Odontodactylus scyllarus*) predates on molluscs and small fish by using feeding appendages (stomatopods). In a recent paper, Patek *et al.* (2004) presented data on the phenomenal velocities and accelerations at which these appendages. Peak velocities ranged from 14-23 m s^{-1} and accelerations from 65-104 km s^{-2}. The duration of the strikes was found to be around 2.7 ms. The theoretical power requirements for such events are around 470 kW kg^{-1} of muscle, far exceeding known power production capacities. Patek *et al.* (2004) identified that the most likely scenario is that these animals store energy during muscle contraction in a 'spring' and this is released by a catch mechanism when maximal muscle contraction occurs. In this instance, the 'spring' is thought to be a saddle-shaped sheet of cuticle.

2.1.2 *Elongation- tongues and tentacles*

Tongues and tentacles give rise to challenges in both deployment and retraction. Most research has been carried out on two systems; the tentacles of a cephalopod mollusc, the squid, and a lizard, the chameleon. Both systems are best characterised by the term 'muscular hydrostat' in that there are no rigid skeletal elements. Most tongue and tentacle systems elongate by contraction of circular muscles (i.e. those where the fibre angle runs perpendicular to the long axis of the tongue or tentacle). The detailed anatomy of such systems is reviewed by Kier & Smith (1985). The tongue extension and retraction mechanism of the chameleon has perhaps received the most attention in the literature. Elongation is achieved by the action of muscle constricting around a semi-rigid rod, the entoglossal process. Efficiency in projection is achieved by the process having a lubricated surface and by the presence of densely-packed, spiral shaped muscle fibres (Van Leeuwen, 1997). As with the mantis shrimp, power requirements for the observed velocities of projection exceed that theoretically available from the muscles, by a factor of between 5 and 10 (de Groot & Van Leeuwen, 2004) which again suggests that the release of stored elastic energy is vital for maximal power output. Of course, for the chameleon tongue projection is only half of the story, since the tongue and attached prey item need to be withdrawn rapidly to the mouth. The tongue of the chameleon can extend by up to 600%, however, measured force production appears to remain

remarkably constant as the tongue is retracted (Herrel *et al.*, 2001). The chameleon achieves this performance by having 'supercontracting' muscles, that may shorten by 50% (it is the only vertebrate to have such a system) and by having a folded retractor muscle, which extends as the anterior portion of the tongue projects and can be easily stored within the available volume in the buccal cavity.

2.2 Mechanical power amplification

Mechanical power amplification, that is using changes in geometry of the musculo-skeletal system, has been identified as a means of maximizing locomotory performance of animals. Alexander (1995) explored how segmentation of limbs and the angles with which they are bent can alter jumping performance. Vertebrates are typified by using countermovement jumps, rather than the catapult mechanisms employed by insects and other arthropods. By increasing the number of leg segments and elongating tarsi, jump lengths are found to increase. Subsequent experimental studies of jumps made by bushbabies (*Galago senegalis*) reported by Aerts (1998) suggest that a specific sequence of actions cause mechanical 'amplification'. The take-off behaviour of the bushbaby could be characterised as having phases of counter-movement, catapult and squat jump with a late contribution of elastic energy stored in tendons. Theoretical studies of jumping by frogs (Roberts & Marsh, 2003) have implicated elastic energy storage, variable mechanical advantage and inertial loads as the key factors that explain jump performance in these animals.

The modes of high-power jumping in vertebrates differ markedly from invertebrates. Complex co-ordination of muscle group activity, together with elastic energy storage and multi-segmented legs, contrast with the simpler elastic energy-rapid release catch systems used by invertebrates. In jumping insects and spiders, for example, muscle actuation is used to store energy in tendons, elastic deformation of the part of the exoskeleton itself (*locust tibia*) or in specialised "deformable" pads between leg segments (jumping spiders). For biomimetic actuation systems, a combination of a relatively slowly acting muscle-like actuator, coupled with a quickly-released stored or elastic energy seems an ideal solution. Using such mechanisms would provide high short-duration power outputs, for example to right an overturned rover.

Summary- Four ways to maximise performance

1. Store elastic energy in springs and fibres
2. Use clever catches to release actuator at peak force
3. Folding long muscles for storage
4. Mechanical linkages and segmentation

2.3 Actuation in plants

Plant have no muscles, as such, but are still capable of movement. The emergence of a leaf from a bud and the opening and closing of petals in flowers are examples of actuation for deployment. The basic mechanism is both is the structural organization of specialized cells (shape, fibre architecture of cell walls) which, under changes of internal pressure driven by chemical energy, are capable of changing shape, transmit and amplify deformations. These examples of deployment are relatively slow but there are several examples of faster response (Simons, 1992). *Mimosa pudica* folds it leaves or stems when touched or shaken; the extent of folding depends on the

intensity of the stimulus (this plant provides also an example of contact sensing). Extremely fast movement/deployment occurs in the venus fly trap (*Dionaea muscipula*) which can close and trap its insect meal in a few milliseconds. Often, as in the case of animal jumping, high power densities are achieved through storage of energy from the actuators (expansion of cells and tissues due to turgor pressure) into elastically deformed structures and then release via some kind of triggering the system (Simons, 1992). As well as reversible actuation, plants have also evolved irreversible actuation mechanisms, mostly associated with seed dispersal. These are "one-shot" devices capable of high power delivery (explosive release in many cases) in order to propel seeds from pods several metres away from the parent plant (the fern *Dryopteris, Erodium*, *Cyclanthera explodens,*). The "actuation" is effectively carried out by releasing the stored elastic energy due to shrinkage of tissues on drying and converting it into kinetic energy.

2.4 Pressure sensing in biology

In both instances, the pressure/contact sensing function is primarily carried out by external tissues such as skin or cuticles. On contact, these fairly compliant structures deform locally owing to their relatively low stiffness and the deformation in converted into a signal. In animals this requires integration with a nervous system. In plants the signal is believed to be transmitted via chemical ionic transmitters released by the deformed cells and action potentials generated by the cells. The deformation of the cell wall under contact pressure is transmitted to the plasma membrane which can change its permeability to ions and water. Channels open under the imposed stretch and potassium or and calcium ions cross the membrane generating an action potential in the form of a voltage spike. The electrical signal is transmitted to neighbouring cells and, in *mimosa pudica* for example, eventually reaches the "motor cells" at the base of the leaves. When stimulated, these cells open water channels to dump their internal turgor pressure, collapsing the leaves. Recovery, i.e. redeployment, requires a few minutes during which time the pressure in the motor cells is increased, allowing them to re-inflate and support the leaves in the desired configuration.

3. POLYMER ACTUATOR MECHANISMS FOR EXPLOITATION IN SPACE

3.1 Introduction

There is a constant drive to reduce the mass and power consumptions of space travel vehicles and the devices placed in space serve to perform increasingly complex tasks. Several of these key constraints can be met through miniaturisation but it is clear that significant limitations occur via this route. Consequently novel designs for surface and space travel based upon unique technologies, such as new types of actuators and other motion systems, 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. 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

(Huber *et.al.*, 1997) 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.

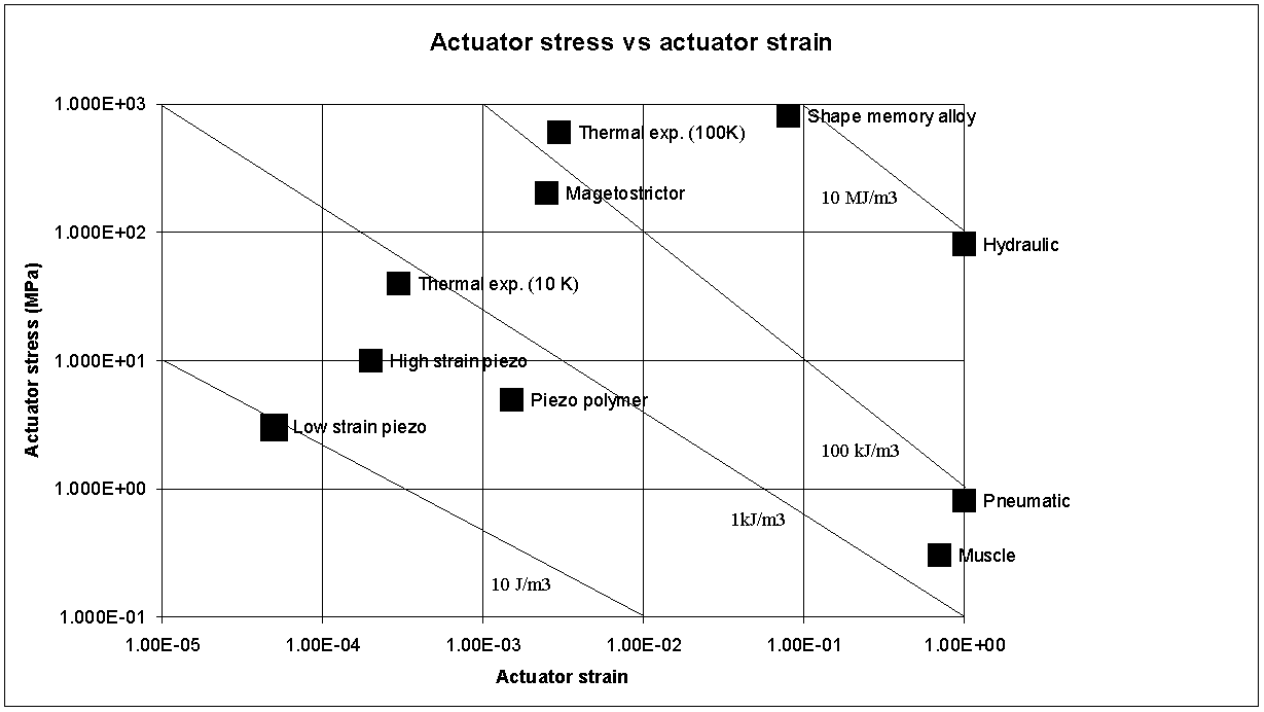

Figure 1: Actuation stress versus actuation strain for various actuators. The sloping lines from left to right give an indication of the energy storage capacity per unit volume of the various actuators (Adapted from Huber *et al*., 1997)

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 (EAPs) have been developed which can be stimulated to produce a substantial change in size or shape. The large stimulated displacements that have been observed 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.

Considerable progress still needs to be made with EAP technologies before commercially viable applications can be developed, other than in the area of piezoelectric polymers. The majority of, if not all, the EAPs under current study have been synthesised or prepared by the investigators themselves. To make progress a multidisciplinary approach is essential with chemists, physicists, materials scientists and engineers all providing key inputs. The generation of specific properties within the material is crucial and the actuator system itself needs to reflect the strengths of the material properties. Moreover, in contrast to many motion systems, the EAP itself may be able to provide a sensing mechanism.

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.

3.2 EAPs and Space Environment

Space presents a challenging environment with many extremes of temperature, pressure, radiation and energetic particles. However, it is an environment in which the successful operation of highly complex instrumentation has been achieved and in limited situations humans and other living species have worked with the minimum of complications. As well as the limitations imposed by the space environment on the ability of EAPs-based devices to perform (high and low temperatures in particular) the lengths of journeys to mars, for example, and the time of residence on the planet will require extended lifetimes of the materials used with minimum degradation in the given conditions.

The two main environments are firstly within an enclosure with control of one or more of temperature, pressure, gravity and radiation and secondly unenclosed with variable environmental conditions with additional factors such as radiation and particulate fluxes. All systems will be subjected to the first in terms of delivery to space and some will deployed in an unenclosed environment.

Unenclosed temperatures vary from 4K in general space to between 80K and 390K on the surface of Mars or the Moon. The temperature is largely dependent on the exposure to solar radiation. The lower end of this temperature range lies outside the conventional operating range of polymeric material systems.

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 magneto-spheres 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 (Ivanov, 1992, Clegg, 1991, Holmes- Siedle and Adams, 2002) 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 effects 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 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 50 μm, 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.

As far as temperature is concerned, Table 1 gives a summary of the situation with respect to the classes of EAPs discussed in more detail in this report. 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 close 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.

Table 1: Functionality of EAPs in space temperature environments

	Dielectric Elastomers	Polymer Gels un-enclosed	Conductive Polymers	Liquid Crystal Elastomers	Piezoelectric Polymers	Shape Memory Polymers
Moon - shade -150 C	Y	N	N	N	N	Y (internal heating / shielding)
Moon – sun + 140	Y	N	N	N	N	Y (shielding)
Moon – mean - 25 C	Y	Y (?) Using non-acqueous solvents	Y(?) Using non-acqueous solvents	N	N	Y
Mars – shade -143 C	Y	N	N	N	N	Y
Mars – sun + 30	Y	Y	Y	Y	Y	Y (shielding)
Mars – mean +60 C	Y	N	Y (?)	N	N	Y
Deep space Shade -270 C	Y (?)	N	N	N	N	Y
Deep space Sun +125 C	Y	N	N	N	N	Y (shielding)

The table does not take into account the possibility of temperature control. If this is included, then a wider range of materials becomes available. The use of shielding to reduce exposure to solar radiation simply minimizes the upper temperature but does not provide the temperature control required for gels, liquid crystal elastomers or piezoelectric polymers. The soft nature of some materials (gels, elastomers) may facilitate the function of self –regulation of temperature.

3.3 EAPs and Actuation – General

EAPs are rich in variety in terms of the basic actuator mechanism, the strength and extent of the displacement, the environmental needs and the complexity of synthesis or construction. We identify three basic groups involving *electronic interactions*, *ionic interactions* and *phase*

transitions with associated conformational changes. We give three examples to illustrate the diversity of EAPs

Active polymer gels by themselves fall typically in the low stress (low force)-high strain group, together with muscle (De Rossi *et al*., 1991; Gong *et al*., 1994). Their elastic modulus in the swollen state is low, typically of the order of 1000 Pa and, consequently, the forces that they can generate in unconstrained conditions are low. Measured values of force generation are about 1N/g of swollen gel. Isotropic volumetric free swelling can be very large indeed, with swelling ratios of 10-12 (Tanaka et al., 1982) but is omni-directional owing to the isotropic behaviour of the gels. Differential swelling, and hence bending of beam or plate-like shapes can be induced by charge separation techniques in some instances. Gels incorporating conductive polymers such as polypyrrole can be cast in film form over a thin and flexible conductive polymer film (Otero, 2000). When exposed to an electrical field a current passes through the EAP, promoting expulsion of solvated counter-ions. The EAP shrinks and the bi-layer structure bends. An alternating external electrical field can induce bending oscillations (Otero, 2000). Small demonstrators using this approach have been made without great difficulty but the forces that can be generated are extremely small (because of the very low modulus of the system and the necessary small thickness of the EAP to ensure a fast response)). Although the ability to induce movement by non-contacting and controllable electrical fields is attractive, these systems are still rather delicate and complex to "package" into a self-contained unit. In many respects swollen active polymer gels behave like soft elastomeric materials. In order to generate higher forces, at the expenses of reduced deformability, taking advantage of their swelling potential and virtual incompressibility, the expansion of active polymer gels must be partially confined in order to convert chemical energy into useful external work. This is analogous to the free expansion of a gas that cannot produce useful work.

Dielectric elastomer actuators exploit the electrostatic Maxwell stress experienced by all dielectrics. These are dry materials based on relatively soft elastomeric films. Essentially the device is a capacitor in which the electrodes are attached to the polymer film. Upon application of a voltage the unlike charges on the opposing electrodes attract each other which reduces the film thickness. Since such rubbers deform at almost constant volume this leads to an expansion of the area of the polymer film. Furthermore the like charges on each electrode will repel each other tending to lead to an expansion of the electrode. There is a built in amplification process since as the film thickness decreases the electric field strength increases. As a consequence the actuation is non-linear with a strain approximately proportional to the square of the applied voltage. Strains of up to 400% have been observed in acrylic elastomers exerting a pressure of ~ 7 MPa (Kornbluh *et al*., 2000) Such systems have the highest energy densities observed for any EAP but the voltages required may be as high as 5kV.

EAPs based on conducting polymers utilise mass transport of ions into and out of the polymer. Two key requirements are an E-field driven diffusion mechanism to transport metal ions into the polymer and polymer conduction to get electrons into the polymer to generate this field. The metal ions in the polymer can then cause a shape or a stiffness change in the polymer. In both cases the polymer change can be used to generate mechanical work. Such materials have been widely fabricated as bending actuators. Polypyrrole and derivatives and polyaniline based systems have been extensively studied (Chandrasukhar, 1999). However, the development of new monomers which can be used to tailor the conduction level and yield new material properties needs more

research. These activator types exhibit modest strains of ~ 10% but can develop high pressures, for example, 450M Pa (Meijer et al., 2002). However, the overall response times are relatively slow.

3.4 Physical and Chemical Mechanisms

In principle there is wide variety of active polymer systems which can be employed in space related applications. We can classify these either in terms of their *mode of operation*, as in Table 2, or in terms of the *molecular level mechanisms* involved (Table 3) or in terms of the *types of materials*. For the purpose of this study, the EAPs are discussed according to the molecular mechanisms responsible for shape change, actuation and sensing. This allows better comparisons between different systems in relation to advantages and disadvantages.

Table 2

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

Table 3

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*

3.4.1 *Mass/Ion Transport Mechanisms*

3.4.1.1 *Conducting polymers*

One of the first viable artificial actuators utilising conducting polymers was reported by Otero *et al.* (1992) and this polypyrrole (PPy) system mimicked the action of natural muscle. Since this report, 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. Each of these actuator types possesses their own respective advantages and limitations and these characteristics will be highlighted below by analysis of notable examples from the literature.

Three main polymer types have dominated research 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 predominated.

Polypyrrole

The utilisation of volume change of electroactive polymers was first described by Burgmayer and Murray (1984) in which the permeability of PPy membranes could be increased by several orders of magnitude by polarizing the membrane under different potentials. The volume change in electroactive polymers arises as a consequence of the movement of ions present in the electrolyte solutions in which the polymer is immersed into or out of the polymer matrix. For example, in the case of PPy that is doped with very mobile small anions such as ClO_4^- in an electrolyte solution that features both mobile cations and anions, the application of a potential across the polymer matrix will result in the insertion and transfer of ions out of the polymer in order to maintain electroneutrality (see Figure 2 for PPy). As the PPy matrix is oxidized (thus producing positively charged PPy) anions flow into the polymer to neutralise the charge thus formed. In solution, anions and cations are solvated by solvent molecules and as the anions insert into the oxidised polymer they 'drag' the associated solvent molecules into the solid matrix resulting in an increase in volume. Counter to this effect, when the polymer matrix is reduced, electrons flow into the polymer to neutralise the positive charges on the polymer and thus the anions flow rapidly diffuse out the polymer matrix and thus its volume contracts.

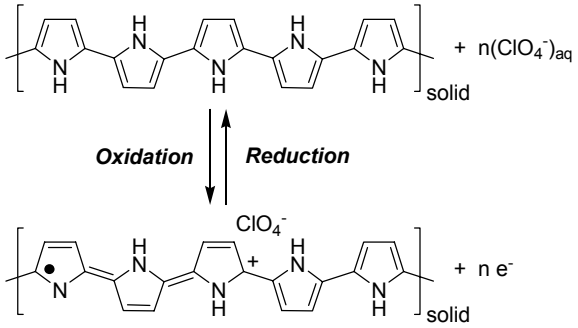

Figure 2

The rate of ionic transfer into/out of the polymer matrix under applied potentials is dependent upon the size of the anions and cations, their solvation shell, the applied potential and the thickness of the polymer film.

Polyaniline

Volume changes of polyaniline (PANI) films under the application of electrical potential was first determined by Okabayashi et al. whilst working in the solvent propylene carbonate. Indeed, weight changes under applied potentials increased up to eight times when working with the electrolyte

system $LiClO_4$/propylene carbonate. PANI undergoes volume changes as a consequence of its electrochemical oxidation/reduction under acidic conditions. The emeraldine form of PANI is oxidized under these conditions (see Figure 3) to afford the corresponding pernigraniline and leuco-emeraldine salts, respectively.

The redox reaction occurs in conjunction with the flow of protons and electrons into the polymer matrix.The structural conversion of the emeraldine salt form to the pernigraniline salt that features quinoid rings effects significant strain upon the polymer matrix with a concomitant compaction of the solid polymer.

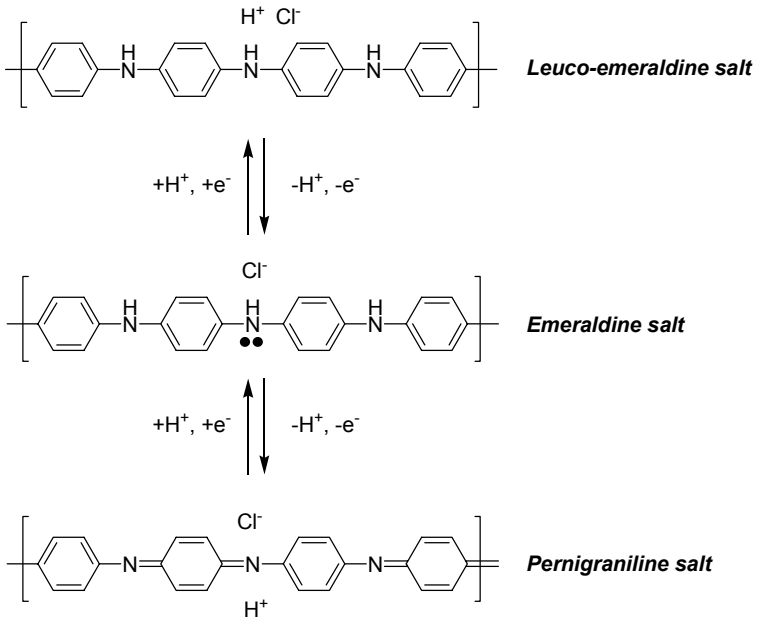

Figure 3

Polythiophene

In contrast to PPy and PANI, polythiophene (PT) has not been as extensively studied but are receiving increasing attention in the search for novel electroactive polymer actuators. However, polymethylthiophene has been shown to undergo volume changes as potential differences were applied. The volume changes were not as dramatic in observed for PPy, this characteristic was attributed to the fibrillar morphology of PT when compared to the random compact structures found in PPy. The mechanism of volume change directed actuation of PT differs from that found in the case of PPy. In this class of polymer, intercalation of solvated anions or cations is not solely responsible for volume changes of the polymeric matrix. PT oligomers are relatively flat macromolecules and it possible for these systems to form extended arrays in the solid state via π-π

aromatic stacking interactions. Upon oxidation, these π-π aromatic stacking interactions are increased and consequently PT systems contract upon oxidation which in turn promotes large strains.

3.4.1.2 *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 effected 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 which can be used as magneto-actuators. The main problem with gels is that their response time is a diffusion controlled process which depends on the surface area to volume ratio of the device. In order to achieve fast response times (less than 1 second) the diffusion distances should be of the order of 1 millimetre or less. However, these small dimensions will limit the force generation (which is proportional to the volume or mass of gel) but this can be compensated by having a large number of small elements acting in parallel. It is possible to use current textile processes to make very small diameter fibrous braided structures (for partial confining of the gel and conversion of isotropic swelling into a directional one) and to polymerise the gel inside the braid. This approach has recently been investigated in the laboratories of the authors of this report.

3.4.2 ***Polarisation Mechanisms (dielectric elastomers, piezoelectrics)***

3.4.2.1 *Dielectric elastomers*

Dielectric elastomers in their simplest form are elastomeric or rubber materials which 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 force f, which is developed is relate to the electric field E by:

$$f = \varepsilon\varepsilon_0 AE^2 \qquad (1)$$

where A is the area and ε the relative dielectric constant.

The stress developed, (f/A), is often referred to as the Maxwell Stress. In certain cases the dielectric constant depends upon the strain and in which case there is an additional component to the force due to electrostriction. Whereas the Maxwell Stress is always normal to the electrodes, the electrostrictive effective depends upon the components of the full permittivity tensor. There may be advantages in pre-straining the elastomer.

The basic elastomer is based on silicon-oxygen polymer chain which exhibits a remarkably low glass transition enabling operation over an extended temperature range of 173K to 533K. Strains of 380% and 63% have been observed in acrylic and silicate based systems exerting pressures of 3.0 to 7.2 MPa. The response of these systems is very fast. The simplicity of the mechanism in dielectric elastomers would allow other characteristics such as operating temperature range or radiation resistance to be more easily optimised for space applications. In particular low glass transition temperature materials coupled with high molecular mobility would allow this type of actuator to provide a reasonable performance over most of the proposed temperature range.

We believe that dielectric polymers are the best short-term candidates for space applications in spite of some issues to be resolved in relation to the electrical stimulation (voltages needed and ease of field generation for shapes which deviate considerably from flat sheets, such as fibrous elements for example).

3.4.2.2 *Piezoelectric Polymers*

The discovery of piezoelectric effects in polymers and the development of polyvinylidene fluoride dates back over thirty years. Since that time a number of alternatives approaches to coupling dielectric polarisation to mechanical strain and these involve the apparently simple idea of an amorphous rubber through to complex liquid crystalline polymers. The piezoelectric effect involves the generation of mechanical deformation upon the application of an electric field. It 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) which 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. We can identify four key elements for a piezoelectric material, the presence of permanent dipoles, the ability to align these molecular dipoles, the ability to sustain this dipole alignment once it is achieved and the ability of the material to undergo large strains.

<u>Semi-crystalline Polymers</u>

PVDF is a semi-crystalline polymer which exhibits a piezoelectric strain coefficient of ~ 28 pm/V. It is commercially available but the preparation of devices involves a series of deformation and poling procedures. Compared with the main ceramic piezoelectric material, Lead Zirconium Titanate, it exhibits a lower strain coefficient (x 1/7) but a higher stress coefficient (x 20). The temperature range is limited by the crystal melting point (~175C) and the glass transition of the amorphous component (~ 35C). Copolymers of polyvinylidene fluoride have attracted attention since they do not require mechanical deformation as in the case of PVDF to yield the polar crystalline phase. The temperature range is slightly extended upwards but the strain coefficient is

lower (~ 12pm/V). However, some researchers have developed so-called single crystal samples which exhibit a substantially higher effect with a strain coefficient of ~ 38pm/V.

Biopolymers

Biological polymes such as keratin, collagen, chitin and DNA exhibit modest piezoelectric effects which are attributed to the internal rotation of polar groups attached to the asymmetric carbon atoms in the backbone.

Amorphous Polymers

Amorphous polymers can be induced to exhibit a piezoelectric effect by electric field poling the material at temperature above the glass transition and then retaining the polar order by quenching to below the glass transition temperature. Clearly such materials require a glass transition temperature above operating temperature in order to maintain poling and the presence of polar groups. A variety of commercial polymers exhibit modest piezoelectric effects. Copolymers of polyvinylcyanide and polyvinyl acetate are amongst the most promising with a temperature range up to ~ 170C.

Liquid Crystal Elastomers

The basic molecular organisation of a liquid crystal elastomer is shown in section 3.4.4.1. The key to the observation of piezoelectric effects is the presence of a ferroelectric phase, the chiral smectic C* phase. The presence of the network allows the reorientation of the polar groups to be coupled to the macroscopic dimensions of the sample. These are specially design and synthesised materials which exhibit the piezoelectric response over the range of the smectic C* phase (20 – 100C). The piezoelectric effect is similar to that observed in amorphous polymer systems.

Polymers are complex molecular materials which exhibit a number of motional transitions. The glass transition is the point at which the material transforms from a glass to a fluid, although the viscosity of the latter is strongly dependent on molecular length. Below the glass transition will be other molecular motions, such as side-group rotations which are also frozen out as the temperature falls. Some of these motions are important for the operation of piezoelectric materials and the operating range will depend on other factors as well as the glass transition. Crystallinity also inhibits motion as is widely used in thermoplastic products based on polyethylene etc. Polyethylene has a very low glass transition but is solid at room temperature due to the crystallites, even though some of the material is still effectively a liquid. Cross-linking will raise the glass transiton temperature.

3.4.3 *Molecular Shape Change Mechanisms*

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 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.* (2002). This is an example of an ionically driven system which of course can be activated electrically.

The coupling between the orientational order of the liquid crystal phase and that of the polymer backbone in a liquid crystal elastomer (see section 7.1) leads to a temperature dependence in the macroscopic shape of monodomain nematic elastomer samples. These shape changes depend upon the anisotropy of the polymer chain which is controlled by the level of liquid crystal order. The extent of variations depend upon the chemical configuration, changes of 10% to 100% have been observed within the liquid crystal phase range. The materials are soft with a modulus ~ 1MPa. For most materials there is a region of linear dependence of the shape change with temperature. Such systems require the addition of heating arrangements. Davis and Mitchell at Reading University (unpublished work) have explored how this might be achieved using an internal conducting polymer network; other approaches are possible using fibres or wires. An interesting possibility is the use of light sensitive molecules to control the state of order rather than temperature. Space environments have fairly unrestricted to light in the UV and visible ranges and there is considerable scope for development.

Future developments

The parallels with biology and the increasing complexity of synthetic macromolecular chemistry offer considerable scope for future developments especially in areas where a multifunctional process is utilised for actuation. One example is to drive a chemical reaction using electrical control, the changes in chemical energy leading to a conformational changes of the polymer molecules and hence to shape change (Osada, 1995; Otero, 2000). It is noticeable that nearly all current actuators are single mechanism devices. There are no specific examples of an electroactive actuator system which uses electrical energy indirectly. This is an area for future development. It would be possible to vary the environment in a gel using electrically stimulated reactions which would induce a variation of shape or stiffness.

3.4.4 *Phase Change Mechanisms (liquid crystal elastomer, shape memory polymers)*

3.4.4.1 *Liquid crystal elastomers*

In the previous section we discussed how changing the shape of a polymer conformation could lead to macrocopic shape changes by coupling the chains in to a network. In this section we explore how this is achieved in materials where the trigger is a change in phase.

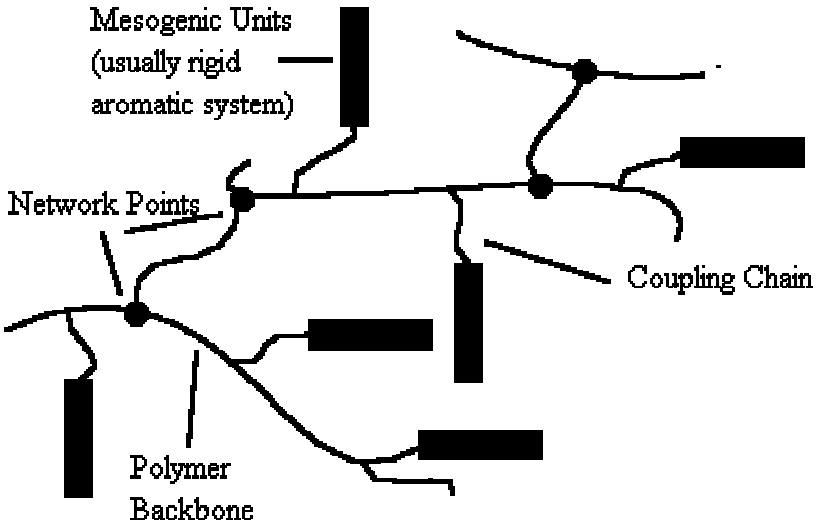

Figure 4

Liquid crystal elastomers are essentially polymer networks which 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.

Although there is considerable scope for the preparation of liquid crystal elastomers, most have been prepared using siloxane or acrylate backbones. The former exhibit larger (~ 30%) shape changes than the acrylate systems (10%). These shape changes may take place abruptly at the transition temperature or on a continuous basis over an extended temperature range as discussed above. The key to exploiting these shape changes is changing the state of the material and this can be done by heating or by using light sensitive materials. In other words, activation must be incorporated in to the material. Stresses of up to 100kPA has been developed on passing through the nematic to isotropic transition (Tajbakhsl and Terenfjev, 2001).

The mechanical properties of liquid crystal networks are unusual and a number of soft modes have been predicted. Application of electric fields to a nematic liquid crystal elastomer could lead to macroscopic shape changes. However, the electrical energy that can be coupled in is too small.

Mitchell and co-workers sought to reduce the effect of the network by swelling the material in a low molar mass liquid crystal compounds and large shape changes of up to 30% where observed on application of fields of the over order MV/m. The response times were < 50ms (Ahn *et al*., 1997; Mitchell *et al*., 1997) but the samples were small ~ a few millimetres. More recently Courty et al have incorporated carbon nanotubes in to a nematic elastomer. These serve to enhance the dielectric anisotropy and the level of electrical energy which can be coupled in to the device. For fields of the order 1MV/m, stresses of ~ 1kPa were developed.

3.4.4.2 *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, by stretching the rubber at a temperature above the crystallisation point and then cooling it in that extended shape will lock-in the deformed material. On heating to melt the crystals, the original network configuration is recovered.

A variety of materials have been employed. One system developed at MIT involves epsilon-caprolactone methacrylate and n-butyl acrylate. By adjusting the composition the shape transition temperatures can be defined. To develop an actuator, methods of heating and deformation are required. These could be integral or external to the material. Materials are available commercially for example Veriflex and this has activation temperatures which can be tailored from -30C to ~ 250C. The material can be deformed by up to 200% and hence large scale actuation is possible. Currently no integrated electrically activated materials is available.

Table 4, 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 have also been included. The values reported are ranges of values obtained from published material.

Table 4: Comparison of EAP's performance for actuation

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

Most EAPs show a significantly higher strain range than conventional materials for actuation but fall short on maximum stress performance compared to those, typically 10 to 100 time less. However, conductive polymers and dielectric elastomers have energy storage capacities per unit mass which are significantly better than those of piezoceramics and of the same order as those of shape-memory alloys.

4. EAP-BASED ACTUATION AND SENSING SYSTEMS

4.1 Conducting Polymers - Deployment In Actuators

Simple actuators based upon electroactive polymers have been formed by employing polymer films. Polymer films such as PPy can be 'grown' galvanostatically from solutions of the pyrrole monomer in a relatively simple but reliable manner. Actuation is based upon longitudinal expansion/contraction of the polymer film as a consequence of the insertion or removal of solvated ions. The majority of these polymer actuator systems have the major prerequisite of working in an electrolyte environment – consequently for 'real-life' applications of these devices ***encapsulation of the actuator system must also be a significant factor***. Encapsulation of such devices impart significant fabrication issues with regard to the actuator systems and serve to increase the number of parameters that need to be considered in the design of the desired device. Pre-doped polymer films have been developed in which the solid polymer matrices have been soaked in the electrolyte solution prior to application – however, vaporisation of the solvent used (especially in the case of aqueous solutions) have significantly limited the lifetimes of the resultant devices (*vide infra*). PPy devices based upon simple thin films have been developed by Della Santa *et al.* (1997) who doped the PPy matrix with benzenesulfonate anions (Lutamer™) and then immersed the polymer in an acetonitrile/water mixture containing 10^{-2} M sodium benzenesulfonate. In its wet state, application of cyclic voltages ca. ±1V the anions are ejected from the matrix and the sodium cations predominate the ion flux into/out of the PPy matrix. The elastic modulus of the polymer decreased by 50 % to *ca.* 660 MPa and forces developed by this simple PPy strip was *ca.* 3 MPa. In a related study, Hutchinson *et al.* (2000) have developed free standing PPy films that were coated with a thin layer of platinum. However, these platinised films were found to be extremely brittle and difficult to analyse.

In a bid to overcome the limitations of aqueous electrolyte systems, Lu *et al.* (2002) have examined the use of alternative solvents in the form of ionic liquids. Ionic liquids are organic/inorganic salts that are liquid at room temperature and possess higher viscosities when compared to aqueous based electrolytes. For example, 1-butyl-3-methylimidazolinium salts were utilised to afford PANI devices that exhibit linear expansions. These ionic liquids were used as electrolytes since they possess desirable properties:- high ionic conductivity, low volatility and environmental stability. Another significant advantage of ionic liquids is that these solvents can be 'tailored' by selection of the appropriate choice of anion or cation. Lu *et al.* (2002) developed PANI fibres were doped with trifluoromethanesulfonic acid and these fibres were able to exhibit energy densities (per cycle) of 10 kJ/m^3 and the specific work performed was 5.6 J/kg. The strain and stress of the PANI fibre was proportional to the consumed charge during the redox cycles – strain to charge ratios of 0.031 % and stress to charge ratios ca. 0.18 MPa mC^{-1}. Furthermore, the fibre was subjected to 10000 redox cycles with minimal loss of strain or stress and consequently

the use of ionic liquids in conjunction with electroactive polymers to afford simple linear actuators represents a significant positive development with respect to the 'traditional' aqueous based electrolytes.

Numerous electroactive polymers that act via a bending action have also been reported in the literature. The seminal work of Otero *et al.* (1997) involved the combination of a PPy film with a layer of material whose volume did not change upon application of the potential. The actual device featured an adherent tape as the non-volume changing material. As the potential was applied, the PPy layer expanded in contrast to the adherent tape and thus the bilayer structure was deformed. The action of these devices has been found to be very reproducible with deviations less than 5% and thin electroactive polymer films result in systems that exhibit more rapid response times as a consequence of the limitation of ionic diffusion phenomena.

Different bilayer combinations have been assessed by Pei *et al.* (2003) with PPy, PANI and poly(3-octylthiophene) as the electroactive components. The inactive material used was polyethylene (PE) and in addition, a range of electrolytes were examined in the resultant bilayer devices. It was found that the PPy/PE bilayers could be bent numerous times without loss of the degree of bending. The optimum electrolyte in this bilayer combination was sodium dodecylbenzenesulfonate and its use afforded the most rapid bending response rates (0.5 mms^{-1}).

Smela and co-workers (1993) have generated bilayers constructed from PPy and a thin layer of gold – these devices were developed into electroactive 'hinges' and even a box that could open and close under electrochemical control. Hinges of this type exhibited significant strength with certain examples being able to lift up to 40000 times their own mass. Combination of metal-polymer composites devices has also opened a route to microdevices and microrobots via manufacture 'on-a-chip' such as the elegant bending devices using micromachining technologies reported by Jager *et al.* (1999, 2000, 2001, 2002) which possessed bending times *ca.* 1-2s.

The majority of the actuators described above were reliant upon the immersion of the electrochemical actuator within an electrolyte solution. This situation is obviously not favourable for transfer into 'real life' applications. As a consequence, there has been significant effort towards developing 'dry' actuators. In most cases the electroactive polymer component will be immersed and soaked in the electrolyte of choice prior to device fabrication. There are still electrolyte containment issues that need to be overcome but several groups have developed interesting devices. For example, Mazzoldi and De Rossi have reported (2001) a PANI based device that was fibrous in nature. PANI fibres were produced by extrusion through a spinnerette. The resultant fibre was soaked in the electrolyte ($HClO_4$) and then embedded with a solid polymer electrolyte (SPE). The PANI/SPE composite was found to exhibit stress values *ca.* 3MPa.

Madden and co-workers (2000) have also developed a dry encapsulated polymeric actuator using PPy thin films and agar gel electrolyte suspensions that act in a linear sense that are capable of generating stresses greater than those of mammalian skeletal muscles. However, the lifetimes of devices of this type were found to be limited (only five cycles were permitted) as a consequence of gas generation and breakdown of the agar matrix under the applied potentials used.

Restrictions

It is quite clear that there are several major limitations to the above devices and further developmental research is required in order to afford reliable polymeric actuators. More research is required on the electroactive polymer systems in order to improve the flux rate of ions in/out of the polymer matrix. Devices of this type will always be limited by ion diffusion rates. Further optimisation of electrolyte types is also a prerequisite – the utilisation of ionic liquids marks a significant contribution towards developing electroactive polymer devices that are capable of operating under the environmental conditions found in space. Use of aqueous based electrolytes is simply not viable under high vacuum conditions (unless the device is encapsulated). Encapsulation is also a major factor in device design and construction – the need to encapsulate these systems leads to complicated fabrication issuses, especially in multielectrode devices. 'Dry' devices are severely hampered by limited lifetimes at present whereas 'wet' submerged systems have been found to be far more reproducible in nature. It may be possible to extend the low temperature range of conducting polymer actuators through the use of ionic liquids. For example alkylpyridinium and 1-alkyl-2-methylimidazolium cations are particular promising. The hexyl derivative is mobile at -70C. This area requires development.

4.2 Polymer Gels – Deployment In Actuators

Gel actuators can exhibit relatively rapid response (0.1 s or less) provided that their surface area to volume ratios are high enough to reduce solvent diffusion times. They are suited to actuator motion-based devices that are not subject to high loads because the low stiffness of the polymer gel limits the force generation. This limitation can be partly overcome by systems of fibre-like polymer gel elements, encapsulated in suitable braided structures and acting in parallel. An artificial gel actuator hand has been developed that is able to hold objects up to 9 g in weight and another notable example is a gel fish that can swim.

Restrictions

Polymer gel actuators have been limited by the primary requirement of being immersed in a solvent system. However, Shiga and co-workers have developed a finger shaped gel actuator that is able to operate without being immersed in a solvent and this device is able to hold objects that weigh up to 0.2 g. Another limitation of gel actuators is their tendency to 'relax' when the applied electrical field is removed. There lower temperature range may be extended by the use of suitable solvent mixtures but extension to high temperatures is quite a challenge.

Future Developments

The key to exploitation of gels is the design of the system in which they are used. For example, at the University of Reading the focus of attention has been in how the stress developed in a gel can be translated into work. We have developed essentially Mckibben type actuators in which the gel replaces the gas (Santulli *et al.*, 2003). There is a clear need to move away from demonstrators to effective systems. The use of ionic liquids may well extend the temperature range to those useful for exposed space actuators.

4.3 Dielectric Polymers - Deployment In Actuators

Kornbluh *et al.* have used dielectric elastomers as the control element in the shape control of large lightweight mirrors for space-operated telescopes (SPEI 5051 143-158 2003)

Restrictions

As the stress generated in a dielectric elastomer is quadratically related to the electric field, such devices are usually used in conjunction with high electric fields. This can be achieved using thin sheets and high voltages. The upper limit to the voltage is determined by the breakdown strength of the material and from a practical point of view by the circuitry available to produce the high voltages. The dynamics of the elastomer are critical to the actuator operation. The modulus of the elastomer may rise substantially if the material crystallises or becomes glassy. Silicone based elastomers exhibit glass transitions ~ -130ºC and are likely to be the most suitable for low temperature space environments. Others, such polyurethanes and acrylates, exhibit glass transitions in the range -30ºC to 0ºC.

The extent to which dielectric elastomers can be exploited depends on methods of enhancing the dielectric constant without compromising the mechanical softness. The current approaches of simple fillers lead to lower performance. An alternative approach is to enhance the role of the electrostrictive effect, essentially a non-linear dielectric constant. Currently little attention is directed at the "off" process in the actuator and there are possible improvements by exploiting an asymmetric operation.

4.4 Piezo-electric polymers – Deployment in actuators

Piezoelectric systems have been widely deployed in a variety of actuator systems. There are plans to use piezoelectric polymers in tiles which can be tilted to control the orientation or angular momentum of a spacecraft (NASA sponsored programme at the University of Arizona). Another area of particular interest is in the control of surfaces for mirrors (Research programme at Sandia National Laboratory). As such materials can sense as well as actuate much of the attention is focused on structural monitoring and vibration control.

Restrictions

As with other polymer based systems, the temperature over which the piezoelectric effect can be exploited by the structure of the polymer. Such systems are most easily exploited in thin films for which poling and other processes are straightforward. In contrast to some other electrically driven functions in polymers, the response time is fast - certainly in the acoustic range, but the displacement is limited and mechanical amplification is often required.

New materials such as those based on polyimides, block copolymer structures and liquid crystal systems are currently under development. In particular the liquid crystal approach offers larger displacements but with synthetic complexity.

4.5 Molecular Shape Changes – Deployment In Actuators

The basic actuator mechanism has been demonstrated a number of times for both linear and bending liquid crystal elastomer based actuators. Large displacements are possible and stresses of the order of 300kPa at an extension of 35% have been reported for an acrylate based system. There are no examples of an integrated electrically driven system for what are essentially thermally activated devices. A light activated swimming fish has been demonstrated using a azobenzene containing liquid crystal elastomers. Forces of a few millinewtons were generated in ~ 100ms with a sample of 0.5mm diameter (Camacho-Lopez et al., 2004).

This is a rich area of development. It is highly likely that the molecular shape changes inherent to a liquid crystal elastomer will form the basic of more complex multifunctional systems, there is still a considerable way to go for even prototypes of such devices.

4.6 Liquid-crystal elastomers - Deployment In Actuators

A particular feature of liquid crystal elastomers is the ability to generate discontinuous shape changes, as first proposed by de Gennes (2002). To date discontinuous shape changes over a limited temperature range have been limited to 5 to 35%. The response times are probably limited by the speed of thermal transfer.

In terms of directly driven electric field liquid crystal elastomers, shape changes of up to 20% were observed by Barnes *et al*. (1989) on swollen liquid crystal elastomers with response times of less than 40ms. No stress values were reported. Very recently a carbon nanotube filled liquid crystal elastomer has been reported, capable of developing a stress of 1kPa for a field strength of 1MV/m.

High speed ferroelectric liquid crystal elastomers have been reported but these exploit very thin films ~ 1μm to achieve the required molecular organization.

<u>Restrictions</u>

Liquid crystal elastomers exploit a subtle coupling between the liquid crystal order and the polymer network. This coupling is only available over a limited temperature range (glass transition to clearing temperature) and may be strong temperature sensitive. However, there is considerable scope for developing higher levels of complexities. Useful actuators will contain at least two elements in terms of the trigger and the driver.

Liquid crystal elastomers are relatively new and there is still considerable scope for developments. The development of useful thermoplastic liquid crystal elastomers is one area of current development. The second is the increasing level of complexity in the material, light activated systems and carbon nanotubes represent two particular examples.

4.7 Shape memory polymers – Deployment In Actuators

Packaged electric field activated materials are currently unavailable but their development is a clear possibility. They offer the prospect of large scale actuations of particular value in deployment. Temperature remains a clear restriction, but the simplicity of the material provides the basis on which an extended temperature range can be achieved.

4.8 Viability in space: Summary

4.8.1 *Temperature*

The wide temperature range required for space applications in unenclosed environments is hardest criteria for polymer-based actuators (see Table 1). Dielectric elastomers, and shape memory polymers meet this requirement with suitable matrix material choice. Conducting polymers and in certain cases gels may be able to meet this requirement through further development and the use of particular solvents. Commercial piezoelectric elements are limited to ~ -15 to 85C and through appropriate chemical design liquid crystal elastomers will be able to cover a similar range.

The operating temperature range of EAPs could be extended by internal or external heating. There is little reported work in this area. Unpublished work at Reading University has explored forming electrically conducting polymer networks within liquid crystal elastomers to provide an internal temperature control mechanism. The addition of internal heating pathways to a material raises questions as to the deformation of that network during actuator operation. Recent work at Reading University has shown that by appropriate design, conductivity can be maintained in elastomeric materials under strains of 50% or more (Peace and Mitchell, unpublished work, Reading University).

External pathways are more straightforward, but for some geometries implementation may be difficult. For example, dielectric elastomers have compliant electrodes which if heated, the heaters would also need to be easily deformed and hence the factors above come in to play. For example, one option to provide a “deformable” heating source would be to have the dielectric elastomers inside a braided structure of electrically conducting flexible wires (similar to the shield in co-axial TV cables). The best shape for this device is a cylinder, i.e. a macro-fibre like structure which incorporates in a coaxial arrangement the inner electrode, the dielectric elastomer, the outer electrode and the heating braid. If properly designed the braid of conducting/heating wires will not interfere with the axial deformation of the EAP. An alternative is the use of infra-red or microwave radiation, which will depend on the compositions of the EAP. Such heating could be supplied remotely for many actuator systems. There is no reported work in this area.

4.8.2 *Radiation and High Energy Particles*

The challenges of UV radiation and high energy particles can in part be met through shielding but these areas need further investigation with respect to active polymer systems. Charging arising from energized particles is likely to be a major problem, especially for “dry” systems such as dielectric and piezo-electric polymers, since their functionality as actuators or sensors depends on electrical charge separation. Conductive polymers and gels may benefit from the shielding that the necessary encapsulation of these solvent-based systems will require.

4.8.3 *Pressure*

The reduced pressure of space environment will have a very limited effect on the EAP materials properties and mechanisms, as such. However, it will limit in part the simpler designs of actuators, especially those requiring encapsulation of solvent, because the evaporation of the solvent will have to be prevented. In general these issues can be resolved by appropriate design.

4.8.4 *EAPs and Sensing*

Many polymers exhibit the tunable properties required for sensing and EAPs are in the forefront of this field. Electrically conducting polymers have been developed for chemical and biological sensors as well as the perhaps for the more straightforward task of strain or stress feedback.

Electrical feedback from stress or strain may active as in piezoelectric systems or passive as in piezoresistive systems. In all cases polymers offer a tunable gauge factor, large recoverable strain ie > 1% typical of non-polymeric strain sensors and compatibility with other polymeric components such as actuators. High gauge factors (fractional change in resistance due to an applied strain) minimise or eliminate the need for costly and sensitive electronic amplification of signals. It fact the development of plastic transistors could lead to an integrated low cost all polymer device. The low cost and ease of deployment are vital factors in the development of distributed sensing system which essential for complete biomimetic mimicry.

The commercially available piezoelectric polymer, polyvinylidene fluoride is widely used as a sensor. It is lightweight, flexible and readily manufactured in sheet form or complex shapes. Compared with ceramic piezoelectric materials it has a limited temperature range. The more recent polyimide based piezoelectric polymers may offer some scope in increasing the temperature range available.

Conducting polymers such as polypyrrole exhibit a linear strain dependence of the conductivity over a strain of more than 1% and the gauge factors lie in the range 0.2 to 5. However, as these are semi-conductors the overall resistance is very temperature sensitive.

Ionic polymer strain sensors based on ionic polymers such as Nafion, a commercial membrane material with metal electrodes, have been developed. Sensing involves ion motion and uses relatively low voltages; a potential of a few volts is sufficient. However, the response time varies considerably, from milliseconds to seconds. A principal advantage is the use in aqueous environments such as medical applications. Semi-commercial examples of ionic polymer sensors are available.

A wide range of piezoresistive systems have been studied. These may be as apparently straightforward as metal filled and/or coated deformable polymers. Recent studies have shown that wire loops are a particular useful conducting fillers. Other approaches involves a simple coating using a metal or a conducting polymer. Peace and Mitchell (unpublished work, Reading University) have shown in recent work that particular metal fillers can lead to very sensitive and highly non-linear sensors. The onset strain for non-linearity can be written in to the material at the preparation stage. This type of piezoresistive material can exhibit recoverable strains of at least

50% if not higher. Mobility of the material is required in the desired temperature. The simplicity of the material function means that this is not a particularly limiting factor and temperatures of -100C can be easily reached.

A variety of other strain sensors have been developed. Most noteworthy are those involving optical feedback such as chiral nematic elastomers. However, these need additional sensors and electronics to be part of a control system and we do not consider them here.

5. EAPs IN SPECIFIC APPLICATIONS

5.1 Smart textiles

Textiles with added functionality over and above the conventional protective purpose may be regarded as smart. In practice, smart textiles may be classified depending upon their functionality and adaptation to the changing situation:

(1) 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.

(2) 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 (Dawson *et al.*, 1999). 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.

(3) 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 2) and 3). 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 (Gregory *et al.*, 1991).

5.1.1 *Use of conjugated polymers for smart textiles*

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 electrons 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 (Rocchia *et al.*, 2003). After a suitable material selection, the goal of obtaining a smart appears to be achievable in two ways:

- Electronic/electrical functionalised fabrics are obtained by depositing the selected materials on it, according to a predetermined geometry (sensing fabrics: Lycra/polypyrrole);
- Fabric are obtained starting from functionalised fibres such as those made of actuating polyaniline fibres (Mazzoldi *et al.*, 2000).

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 (Madden *et al.*, 2001).

In the following paragraphs, the properties of the actuators obtained using conjugated polymers are discussed. The discussion will concentrate then on the aspects of smart textiles technology that appear to be suitable to be used in the envisaged application. For this reason, dry actuators will be considered, which can operate without immersion in a liquid, limiting the effect of constraints related to service temperature, in particular. In addition, the problem of actuator encapsulation, including possible operation at pressures close to vacuum will be considered. Finally, since 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 (Bobbio *et al.*, 2000). Developments of polymer preparation to obtain a fibrous geometry are also reported by the same authors (Bobbio *et al.*, 2000).

5.1.2 *Polypyrrole in textile actuation*

Typically, polypyrrole actuators, starting from the prototype developed by Otero *et al.* (1992), are based on polymeric films doped in water solution with electrolyte (e.g., perchlorate salts), and the actuator is built as a bi-layer, based on the differential thermometer principle. The reversibility of actuation is obtained by the contrasting effects of water and of a polar solvent. Therefore, for the polypyrrole actuators to be viable for the envisaged application, a number of steps need to be taken, such as the include substitution of water with another polar solvent, able to withstand very low temperatures, and modification of the polymer geometry to a fibrous form. This would also allow reducing the response time, which is so far reported to be between 100 and 200 seconds (ARTMUS, 2001). Possible candidates for operation as polar solvents are for example acetone, isopropyl alcohol and ethanol, with freezing point of respectively -94.7°C, -89.5°C and -117.3°C at atmospheric pressure.

It is also worth noting that the implementation of polypyrrole in film from could be avoided when starting the preparation at a molecular level, since it was based on the assumption that polypyrrole had essentially an amorphous structure. In contrast, crystalline fibre structures were observed in

polymerised polypyrrole, although density and size depended on the polymerisation time and the concentration ratio of pyrrole and oxidants (Chu *et al.*, 1995). If the above problems are addressed, using an actuation voltages of ~ 1V polypyrrole based actuators are able to generate large forces per cross-sectional (40 MPa peak) with power to mass ratios of up to 150 W/kg with a relatively low deformation rate, not exceeding 0.1%/s in a 1-10% strain range (Madden *et al.*, 2001). However, higher strain rates, up to around 3%/s, were obtained by increasing the applied potential up to 7V (Lewis *et al*., 1997)

In a study aimed at integration of polymeric actuators into textile fibres, a different principle was used, by coating conventional tensile fibres or fabrics with a very thin layer of polypyrrole. Remarkable properties of strain and temperature sensing were obtained. The main disadvantage of this solution is that settling times are too long, making the fibre unusable for many applications. In addition, large anisotropies in volume change have been observed: for example in DBS-doped polypyrrole, the out-of-plane dimension undergoes a change of 35%, whereas the other dimensions reach barely a 3% maximum. This anisotropy can be tailored exploiting fibre architectures (knitted, braided) to enhance in-plane deformations. The large non-uniformity of polypyrrole behaviour again suggests fabricating thin fibres to better control the strain of the device. Moreover, electrical conduction of polypyrrole layer in textile fibres appear to degrade considerably, up to an order of magnitude in 30 days, which represents a limitation of the technology adopted, although the low air pressure of the application should reduce this effect (Scilingo *et al.*, 2003).

Another limitation of traditional polypyrrole actuators, which is relevant also to obtain smart textiles, is their operation only in bending mode. This limitation was recently overcome, and a longitudinal actuator was developed by applying two oppositely doped polypyrrole layers with a polyacrylamide hydrogel in an attempt to modify the actuator design (Madden *et al.*, 2000). In a subsequent study, comparing performance of polypyrrole actuators with different design, the largest force per unit width was generated using a fibre bundle design, 0.10 N/mm compared, for example, with 0.025 N/mm for laminated films (Hutchinson *et al.*, 1999).

5.1.3 *Polyaniline in textile actuation*

In contrast with polypyrrole, polyaniline has been used in actuator prevalently in a fibrous form. In particular, spun fibres (diameter 100 to 250 μm) were drawn and doped with 1M $HClO_4$ through immersion for 24 h. Elastic modulus of the fibres was 3.5 GPa (dry undoped), 1.5 GPa (dry doped) and 0.7 GPa (wet doped), with tensile strength varying between 35 and 50 MPa. Ratio between strain and exchanged charge density was 6.7% (C/mm^3), with a maximum electrochemically induced isotonic strain of 0.3% and isotonic stress of 3.5 MPa (De Rossi, 1999; Della Santa, 1999). This shows that doping and preparation have still a large influence on the actuation properties, which is a factor to be considered.
In spite of this limitation, a dry linear actuator was obtained based on polyaniline fibres doped with perchloric acid, with a production method based on extrusion through a spinnerette (Croce *et al.*, 1994). The response time was still around 100 seconds, but it is likely to be reduced using fibres of smaller diameter. Also, polyaniline fibres appear to have the advantage of presenting considerable range for properties improvement through preparation. As an example, an alternative polyaniline fibre manufacturing method, wet spinning, was capable of cold drawing fibres to extensions of >500 % with a concomitant rise in electrical conductivity of up to 1500 %, reducing also voids and offering breaking strain again in the order of 50 MPa (Monkman *et al.*, 2000).

5.1.4 *Polythiophene in textile actuation actuator*

Other conductive polymers are being investigated, including polythiophene, which in spite of its more difficult polymerisation, has the advantage of a different actuation mechanism, resulting from stacking of tiophene oligomers upon oxidation, producing a reversible molecular displacement, which promotes large strains (Anquetil *et al.*, 2002). Using electrospinning, polythiophene fibres can be obtained, appearing to be homogeneous and show oligomer stacking, which is promising for actuation (Bianco *et al*., 2004).

5.2 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)

An additional feature of muscles is that, owing to nervous control and its particular structure, it can function as a variable stiffness system, providing a wide range of "effective" compliances.

In considering EAPs for robotic actuation, the type of motion/locomotion envisaged is important. Four main types: rolling, walking, sliding, jumping/hopping. Different *power* requirements, different energy storage and delivery systems and different architectures will be required in the actuators, depending on the type of locomotion.

5.2.1 EAPs as an animal muscle analogue

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 fasicules - 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 (2002) 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.

Shape memory actuators have also been proposed as actuators with muscle like properties and there have been some spectacular failures with trying to make this proposition into a functioning robotic device. Problems relate primarily to the difficulty of extracting heat from the actuator when it is cycled with any speed.

There are some properties of animal muscle that are worth mimicking in a practical robotic system. One property that is very attractive is the ability of the natural muscle to change impedance over a wide range. Thus for some activities the muscles can be co-contracted to provide a stiff system with a high force generating capacity, and this can be rapidly modulated to a low stiffness system to allow compliance with the local environment, for example when opening a door or drawer. 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 arrangements of muscles, tendons, joints etc have undergone a considerable period of refinement, and although may not be optimal for the tasks they are called on to perform, they usually perform at a *high efficiency level*.
- 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.

With this in mind it is interesting that Bar Cohen has proposed a competition of human vs robot arm wrestling as research goal for researchers in electro active polymer.

The following table is adapted from Y. Bar-Cohen Xue, Shahinpoor, Simpson and Smith: 'Flexible low-mass robotic arm actuated by electroactive polymers and operated equivalently to human arm and hand.' Albuquerque, April 1998:

Table 5

Property	***Electroactive polymers (EAP)***	***Electroactive ceramics (EAC)***
Actuation strain	> 10%	0.1-0.3 %
Stress (MPa)	0.1-3	30-40
Reaction times	Microseconds – seconds	Microsecond-seconds
Density	1-2.5 g/cc	6-8 g/cc
Drive voltage	10-100 V/micrometre	50-800 V
Fracture toughness	Elastic, resilient	fragile

5.2.2 *Current applications of EAPs in 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 (ESA papers, plus others). The first of these is the windscreen wiper proposed for the MUSES-CN. 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 (Sahoo *et al*., 2001;Bar-Cohen *et al*., 1998). 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 10 g.

The strength of these two examples is that they could be used in space applications, however it is clear that there is more work needed to realise the true potential benefits of Electro Active Polymers in terms of their energy and power density, and their speed of response, and their flexibility in systems design based on composite structures.

Smela's box – uses a polypyrrole – gold structure to manufacture micro hinges that allow the box to form and close from flat (Smela, 2004 website). See also Jager *et al*., 2000.

Braid II, Braid III (Binary Robotic Articulated Intelligent Device) are actuators that appear to show the efficient use of EAPs vs electric motors. The principle used is to effect a binary shape change of a stack of actuators made from the dielectric polymer VHB 4910 (made by 3M), to

change the proportions of a flexible framework. (Work was done at MIT under the supervision of Professor Steven Dubowsky). The following results published in an undergraduate thesis appear to show the weight advantages of this approach.

Table 6

Specification	Braid III	Braid II
Weight per stage	38g	73.6g
Weight of single actuator	1.2g acrylic film and electrodes	14.0g (magnets and coils)
Max Force	1.5 N	1.4 N
Electrical requirements	5.5 KV - 0.032 mA	3.5 V - 3 A

In this thesis the EPAM actuator that is build and achieves a movement of about 5.5mm but no information is available on the response time and there is insufficient work to back up these claims.

Hopping and Jumping Robots

Hopping has been considered for planetary transport since the early days of moon exploration. Kaplan and Seifert, (1969) proposed a hopping transport to NASA in 1969 but details of this work are not readily available and cannot be reported in depth at this point.

Hale *et al.* (2000) describe more recent work on space based hopping machines for planetary explorations. In this as well as building a prototype mechanism they also identify some considerations for a remote vehicle that is proposing this method for transport.

Although they conclude that a spring is a convenient and robust mechanism to store energy for hopping robots (having considered impulsive actuators, gas expansion and 'other exotic means') they concluded that linear springs are inefficient with only 20% of the energy stored in the spring being realized as kinetic energy at takeoff. They also note that a large percentage of the spring energy is transferred into kinetic energy late in the take-off phase thus if there is a large loss pf energy should the hopper prematurely leave the ground. The energy loss because of four factors: 1) spring inevitably has an end stop and in most cases the large amount of energy that only becomes available towards the end of the cycle is dissipated in the end-stop; 2) the foot mass/body mass ratio needs to be small; 3) linear spring characteristics result in significant energy loss whenever the hopper foot prematurely leaves the ground; 4) slippage of foot on ground (friction cone limits jump distance). To reduce the consequences of 1 and 3 this group introduce the concept of a non-linear spring based on a pantograph mechanism that generates its peak force about 2/3 of the expected extension. The resulting force/extension profile is then similar to that identified in Figure 5.

Since a limitation is dissipation of energy into components within the hopper the authors identify an efficiency measure for the energy storage:

n = hopper kinetic energy at take-off/energy stored in compressed members.

A linear spring is likely to achieve hopping efficiencies of the order of 20% with most of the energy lost to the internal dissipation in the spring whereas 70% efficiencies are possible with their non-linear spring arrangements.

Although they demonstrate a successful hopping robot suitable for planetary exploration they identify several difficulties that must still be overcome. The hopper needs to operate on a variety of terrain ranging from rock or sand. In the latter case there is a danger of transferring significant amounts of the spring energy into the redistribution of the planet surface and little into achieving a greater than g acceleration. Since it is also desirable to move forward it is necessary to angle the force applied by the foot in an appropriate direction. The direction of this force needs to be kept within the friction cone defined by the foot/surface friction coefficient, thus a smooth rock surface may not allow significant forward movements. On landing it is difficult to guarantee that the hopper will land on its foot although this is desirable as some level of energy recovery is then possible.

Should the hopper not land on its foot/feet then it must go through a self-righting procedure. An interesting observation is that the Click Beetle, if it does not land on its feet, lands on its back and then uses release of spring energy in its exoskeleton to achieve a second form of jumping. Other animals take some care to maximise the chances of landing on their feet. For example the locust uses sensors during flight to modulate its wings to increase the chances of a foot first landing.

The planetary hopper of Hale *et al*. achieves an earth-based vertical hop of 0.9 metres and a horizontal distance of 2-2.4 metres. On Mars this would achieve a 2.7 metre vertical jump and a 7.3 metre horizontal jump.

It is clear that energy management will be key to hopping or jumping robot.

- Store energy over period of time and release for the hop (there are numerous biomimetic examples: for example the frog or locust hop).
- Pneumatic or chemical sources
- Potential to recover energy on landing (elastic energy storage like tendons)
- Cyclic hopper (biomimetic example Kangaroos)
    - store energy in spring

The acceleration of a typical hop might follow the trajectory indicated in Figure 5. Considering a linear spring with energy already stored, then on releasing the spring the acceleration of the centre of mass of the robot/animal rises rapidly to that of the spring force/body mass. There upon as the spring releases energy the acceleration falls. If the body velocity is positive when the animal has its leg fully extended then takeoff is possible and gravity dominates the trajectory thereafter (with additional influences from the flow of air around the robot/animal body). Most robots on landing will dissipate the energy into mechanical components, but it is possible to recover some energy back into the spring and where this is possible actuator energy can be conserved.

There are several more examples of hopping robots. Seminal work by Playter and Raibert (1992) at the MIT leg lab is still relevant. Most of the experiments done while Raibert was in charge of research of this laboratory were based on pneumatic actuators where the source of the energy was not required to move with the hopping robot. It is also interesting to observe that Raibert achieved

control of attitude during the robots flight by changing the moment of inertia and hence the angular velocity during flight so in most cases a foot first landing was achieved, although no energy recovery was attempted.

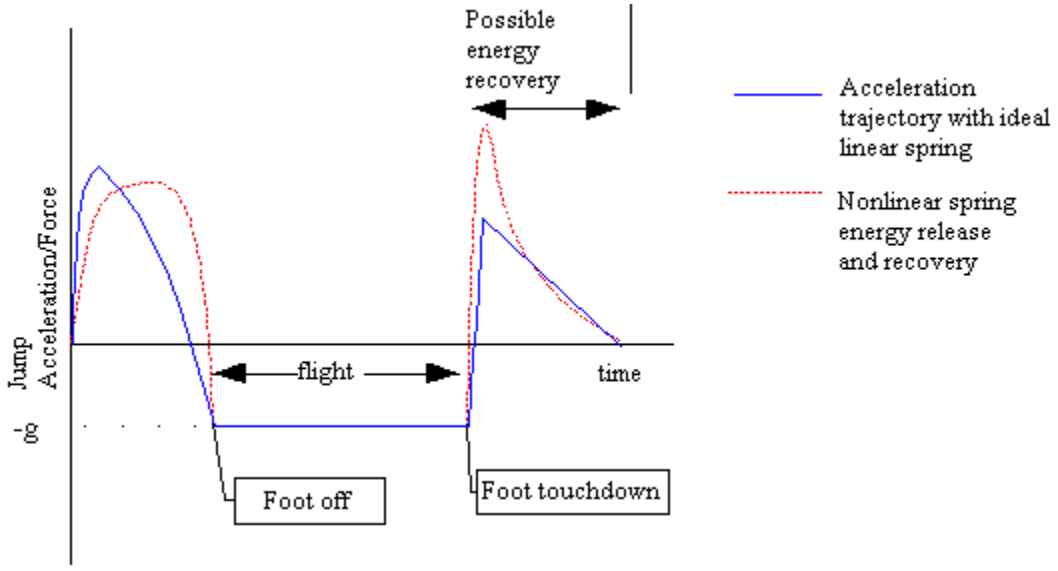

Figure 5: acceleration profile of a hopping robot centre of mass for a single hop jump.

More recent work includes simulations of the hop of a frog inspired robot (Geng *et al.*, 2001) and a hopping robot based on the anatomy of a dog hind leg that stores energy in a tensile spring tendon (Hyon and Mita, 2002). A small surveillance robot developed at the University of Minnesota included a spring foot with a winch windup mechanism (Stoeter et al., 2003). The scout robot is cylindrical so that it can be fired from a mortar-like launcher into a building and once landed can roll on a smooth surface. It can then transmit camera images and other sensed information back to a larger 'Ranger' robot and hence back to a central control. The spring based foot of the scout robots allow the robot to attempt to free itself if it gets stuck as well as to leap small obstacles although there is no control over the trajectory, other than to optimize distance or height prior to deployment.

It is clear that jumping may not be the most effective locomotion style. It is true that it is the gait of choice for kangaroos above a certain speed but they achieve significant energy recovery on landing. However, a jumping robot for planetary exploration may well provide a simplistic method of manoeuvring but with the associated risks of having little control over the landing point and hence a danger of becoming irreversibly stuck.

Walking and sliding robots

There are numerous examples of biped walking robots, and popular examples are the Honda P5 series machines. These use a simplistic control structure that requires the robot to walk with bent knees to avoid the complexity of the singularity when the knee either locks or goes from a foot back configuration (like a person) to a foot forward configuration (like a flamingo). This is a very

inefficient gait mechanism, in terms of the energy per step required. Very few biped walking robots exploit the energy advantages of a locked knee on heel strike although the most appropriate examples are the simplistic walkers that use gravity as the energy source to walk down an incline (will find some references for this).

Multi legged robots are relatively easy to build and a wide range of gaits are possible but these do not tend to be energy efficient in comparison with the equivalent animal.

Snake robots have been explored in past, and are probably worth considering for planetary exploration as they have multiple mechanisms available to move over a range of surfaces and climb a range of objects. A good biomimetic example is the 'sidewinding' action used by rattlesnakes to allow efficient and fast locomotion over sandy soils. They are also an ideal concept for fast acting EAP actuators since they require a large number of degrees of freedom and this is likely to be an area where EAP's will clearly win out over traditional actuators.

Cooperative and reconfigurable robots

Cooperative robots have re-emerged in recent years to explore issues of system redundancy. For example we have demonstrated the mapping capabilities of a team of cooperating mobile robots by simply designing a Kalman filter and treating the team as a single entity. This configuration allows a single robot to be lost to the mission and should this loss be simply due to a communication link problem, the robot can rejoin the group and update the Kalman filter parameters with information acquired while incommunicado.

There are several examples of reconfigurable robots, that is robots built from modules that can reorganise to meet the criteria of the task at hand. Work at Xerox Parc on the Polypod showed a variety of morphologies and locomotions available from a simple robot module. Here the polypod chain can be reconfigured into a suitable morphology to meet the locomotion demands of a particular terrain thus, for example, a continuous loop robot can roll, the loop can split and form into a snake that can 'inch worm' or slide. It can then reconfigure into a spider structure for multi-leg walking or do flip-flops (Yim *et al*., 2002).

Reconfigurable robots have been considered for the construction industry where a scaffolding or structure can be made of reconfigurable modules. This allows easy deployment of the structure and some degree of self repair, i.e. by discharging a faulty module and reorganising around the space then created.

Haptics and Telerobotics

Electro active polymers and novel actuator 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, 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!

Our own work is investigating Electro-active polymers as a method of applying assisting or retarding forces across a human joint. (EU DRIFTS Project) In our case the intention is to reduce the level of tremor for a individuals who do not respond to more traditional drug treatments of tremor. The concept is sound since this is essentially an exoskeleton and the EAP could provide force feedback to the individual to make him/her aware of important local features in a simulated environment, or provide an additional mechanism to explore complex data structures.

5.3 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 EAPs shape change mechanisms and their relatively 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 (Kobayashi et al., 1998, 2000). 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 (Wootton, 1981). 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.

6. Virtual Demonstrator

Deployment of a metre long cylindrical robot.

One possible scenario being considered by ESA is to use EAP actuators to allow a metre long cylinder to hop/jump in mars gravity. It is clear that the power requirements of EAP's are not able to achieve this task directly. However, it is interesting to speculate how EAP actuators, along with a suitable spring storage device might be used. Not withstanding the difficulties of landing, such that a second hop can be attempted, it is appropriate to consider the mechanism used by locusts to jump. The web page by Heitler (2004) as well as publications by Bennet-Clark (1975), Alexander (1995) and others describe in detail the anatomy of the locust hind leg and the presumed mechanism for the jump to occur. In summary the locust uses a large extensor muscle to store spring energy in an adaptation to the exoskeleton called the semi-lunar process as well as in the

apodeme where the extensor muscle attaches to the tibia exoskeleton. In order to retain the energy the much smaller flexor muscle uses a combination of a large moment arm, and a pocket in its body that can catch onto a process called the Heitler's lump to retain the energy in the semilunar process. Once the extensor muscle is fully contracted then the extensor can lift clear of Heitler's lump and the locust can jump. It is clear that this spring storage is highly optimized for the locust because if it is scratched, it will fracture when the locust next attempts a jump or a kick (implying that the stresses in the spring are close to maximum allowable in the hard cuticle material – safety factors are sacrificed for performance). This also points to the fact that the energy release rate from the spring device, to provide the necessary power, is optimized for materials with high *elastic modulus and low densities*, partly because the energy storage per unit mass is increased but also because the speed of sound will by maximum (stress waves cannot travel faster than the speed of sound to release the stored energy). Composite materials such as carbon-fibre reinforced polymers are particularly suitable for these applications.

While in contact with the ground it is reasonable to model the robot/locust as a mass-spring-damper system. If the leg has a length l_0 then prior to take off we have:

$$\ddot{x} = -\frac{K}{m}x - \frac{B}{m}\dot{x} - g = -\omega_n^2 x - 2\varsigma\omega_n \dot{x} - g \tag{2}$$

A Laplace transform with initial conditions gives:

$$s^2 x + 2\varsigma\omega_n x + \omega_n^2 x = -sl_0 - 2\varsigma\omega_n l_0 - g \tag{3}$$

In this formulation the point $x=0$ is where takeoff occurs and the feet leave the ground. If the robot/locust is attempting to clear an object the leg will need to be retracted once airborne. During the initial takeoff period the height of the centre of mass is given by the formula:

$$x = \frac{\exp(-\varsigma\omega_n t)}{\sqrt{1-\varsigma^2}}\left(-(l_0 - \frac{g}{\omega_n^2})\sin(\omega_d t + \phi) - \frac{g}{\omega_n^2}\right) \tag{4}$$

Where $\omega_d = \sqrt{1-\varsigma^2}\,\omega_n$ is the damped natural frequency, $\omega_n = \sqrt{K/m}$ is the natural frequency of the spring (K being the spring stiffness and m its mass) and $\varsigma = b/2\sqrt{Km}$ is the damping coefficient (a value probably between 0 and 0.5). At take off the mass of the robot/locust will increase by the weight of the leg and foot.

Thus far the equations all relate to a linear system so are relatively easy to calculate. Figure 2 shows a typical takeoff in mars gravity where there is sufficient natural frequency in the mass/spring system to achieve a hop. Both locusts and Hale *et al*. (1969) exploit a nonlinear spring to achieve higher takeoff velocities. In both instances the nonlinear spring could be considered as a spring attached to a lever with a variable mechanical advantage, n. It is then relatively easy to show that $\omega_n' = \frac{\omega_n}{n}$ and $\varsigma' = \frac{\varsigma}{n}$ are the modified natural frequency and damping. During the course of the energy release of the spring, the lever arrangement of the locust foot results in this

mechanical advantage reducing so allowing rapid acceleration of the locust body and a higher velocity earlier in the take off process.

Given the above formulation and the well known ballistic formulas relating to trajectory in a gravitational field it is possible to see from Figure 6 the typical simulation of a hop. In this case the leg length is 5 units and the robot/locust achieves just over a further 5 units of height.

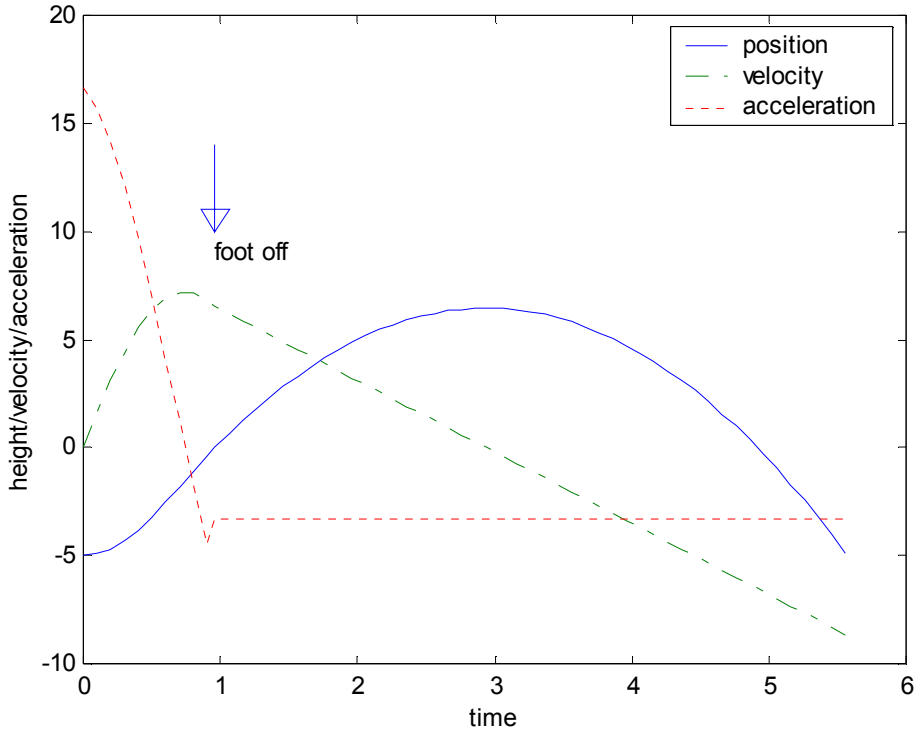

Figure 6: relationship between velocity, position and acceleration in locust

Table 7: Typical parameters of a Locust (Schistocerca gregaria)

Peak acceleration of centre of mass	20g
Weight of locust	2-3 g
Velocity at take-off	3 m/s
Peak force at foot (occurs midway in jump)	30 g (15 g per foot)
Peak force in extensor	12N
Energy needed for jump	10-12 mJ
Energy stored in each Semilunar process	3 mJ
Peak power in muscle	36mW
Power at takeoff	75mW

This approach can be used to investigate the performance of the virtual demonstrator (1 metre long tube) once its mass is known and the height of hop/jump required.

7. CONCLUSIONS

From the information collected and discussed in this study, a number of conclusions can be drawn and challenges identified.

7.1 State of the art for EAP's as actuation and sensing devices

- Of the various types of EAP-type actuators investigated so far, those based on dielectric effects are particularly suitable in view of the relatively large forces and displacements they are capable of and of their response time. Their main drawback is the voltage level required and the risk of "electrical" breakdown. The offer also the advantages of not requiring encapsulation and greater low-and high-temperature performance than other systems. Low pressures, low gravity of space environments have limited effect on their performance. Protection from specific forms of radiation may be required to prevent degradation.
- Strain sensing functions can be implemented via a wide range of EAP systems, depending on deformability requirements to detect contact, contact pressures, areas of contact, etc.;
- Developments in obtaining the EAPs in "fibre" form for actuation are comparatively limited but, if achieved, fibres will allow for a great deal of design flexibility, diffuse actuation, differential local actuation, integrated clothing applications, etc.

7.2 *Challenges*

- Limit degradation of EAPs to extend life and integrate temperature control systems
- Optimise and integrate composite design of EAP and associated "stimuli" delivery, especially for fibre-like structures
- Increase power delivery by using EAP actuator in conjunction with elastic spring element: EAP to "charge" the spring which can then be triggered to deliver high power levels. This can be best achieved using composite materials (glass or carbon fibres) which have very high elastic strains, relatively high moduli and low density. For example, the energy storage capacity per unit mass of three classes of materials is: Steel (@ 1.0% strain) = 1346 J/kg, typical Glass Reinforced Composites - GRC (@ 1.5%) = 3900 J/kg, typical elastomer (@ 5.0%) = 3 J/kg, @ 10% strain = 12.5 J/kg, @ 20% strain = 50 J/kg, @ 50% strain = 312 J/kg and @ 100% = 1250 J/kg. It is clear that in order to approach GRC the elastomers need to work at very high strains.
- Fast delivery of energy for jumping and hopping actuation requires also materials with high modulus/ density values which result in high speed of propagation of stress waves and hence high strain energy release.
- Combinations of EAP's structures and composite spring elements have received comparatively little attention. Several options are possible, such as direct combinations within "sandwich" type structures or connected via lever systems for amplification, as in many biological examples (elastic buckling of locust tibia, for example, to store muscle energy in stiff exoskeleton and rapid release with high accelerations achieved).
- Design and integration of non-linear springs for higher efficiency.

- Storage of part of energy in spring elements between successive hops/jumps
- Indirect use of polymers for electrical actuation
- Production of radiation damage tolerant EAPs
- Effective encapsulation
- Deformable anisotropic dielectric polymer-fibre systems to obtain Poisson's ratios higher than 0.5 in order to increase the strain induced by the electric field.
- Auxetic EAP's with negative Poisson's ratios may be beneficial. They will contract laterally during compression and may be suitable for small volume packaging of pre-strained EAP actuator for deployment)
- Need small scale creatures (fabrication techniques and technologies e.g. base on laser cross-polymerisation/fusion as in rapid prototyping techniques
- Cooperative and re-configurable strategies might be worth considering, e.g. polypods

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9. Laboratories Involved in EAPs Research and Development

Laboratory	Contact Person	Main Research Interest
University of New Mexico	M. Shahinpoor	Actuators (IPMCs/IPCCs)
Reading University	G. Jeronimidis	EAPs actuators, robotics
Università di Pisa	D. De Rossi	Smart textiles
Risø National Laboratory	P. Sommer-Larsen	EAP actuators
MIT	R. Langer	Polypyrrole actuators
JPL, Pasadena	J. Bar-Cohen	Artificial muscles
SRI International	R. Pelrine – R. Kornbluh	Multifunctional actuators
Basque Country Uni., Oviedo	T. Fernandez Otero	Polypyrrole actuators
UT Dallas	D. Hanson	Humanoid robots with EAPs
Micromuscle AB, Sweden	E. Jager	Biomedical actuators
EAMEX Corp., Japan	K. Onishi	EAP actuators
Hokkaido University	Y. Osada	EAP actuators
University of Tokyo	M. Otake	EAP robots (starfish)
EMPA – Zurich	G. Kovacs	Dielectric polymers
University of Nebraska	J. Li	Electrostrictive composites
University of Manchester	S. Baurley	Smart textiles
Univ. de Los Andes, Bogotá	M.T. Cortés	Conductive polymers
Queen Mary College, London	A.P. Monkman	Polyaniline fibres
University of Zurich	R. Pfeifer	Autonomous robots