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Concept design of novel bio-inspired distributed actuators for space applications

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ABSTRACT

Space technology is often considered very conservative: reliability and robustness are main drivers. Novel concepts coming from research activities, however, are the lymph for the development of successful and competitive new space system solutions. The aim of this paper is to present new concepts and ideas inspired by natural systems with distributed actuators embedded in their structure for possible use in space operations. Technological solutions for long term future implementation are proposed and analyzed in order to assess both feasibility and performance of such novel concepts. Peristaltic muscle movements obtained by the use of dielectric electroactive polymers is proposed as one of the most promising solutions. Experimental performance of single discrete electroactive polymer unites are presented. Directions for future implementations are proposed.

1 Introduction

Animals and plants have a wide variety of sensors and actuators customized for particular purposes and uses. Some bio-perceptive systems have the particular characteristic to be distributed along surfaces and not localized in small areas. This feature makes it possible to have efficient actuators that do not influence the shape and the macroscopic characteristics of organs in which they are located. An example of distributed actuators concerns motile cilia that synchronously beat attached to cell's surface. Another example of distributed mechanisms is the peristaltic wave motion which enables the intestine to transport food and digest it. Several other distributed systems exist in nature with multiple functions for the different uses. Space systems usually rely on simple and reliable mechanisms since repair operations in space are risky and expensive. However, new emerging technologies might sensibly enhance performance of conventional systems while still meeting reliability requirements.

This paper shortly considers natural systems having distributed actuators and mentions possible futuristic space applications of bio-inspired distributed systems of actuation In the fourth section, promising technologies for the development of bio-inspired distributed actuators are considered and in particular, smart materials are investigated. The fifth section investigates the potential use of electroactive polymers in the space environment. The sixth section presents three possible configurations for implementation and shows experimental results of elementary actuating units suitable for the development of the proposed bio-inspired concept designs. The paper concludes suggesting future directions for further developments.

2 Biological concepts for distributed actuation

Surfaces with distributed actuators (DA) are present in nature in different forms and used for various purposes. In this section, two natural distributed actuated systems, in which the authors consider the most promising for an engineering biomimetic approach, are presented and discussed.

2.1 Natural Cilia

Cilia are organelle made of parallel microtubules that can be considered extension of cells' plasma membrane. Fig. 1 shows a cross and longitudinal section of a cilium (source: [1]).

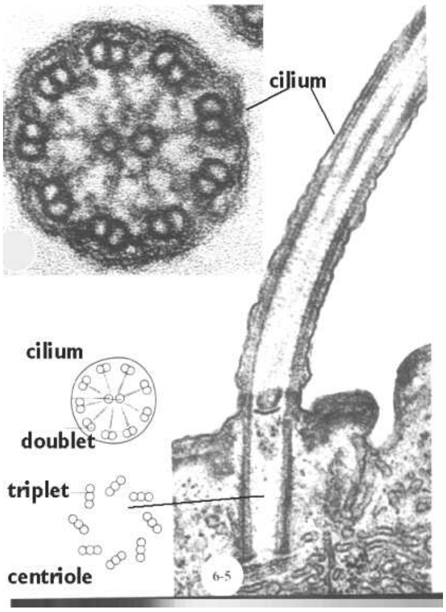

Fig. 1 Cross and longitudinal section of a cilium. (Source: http://cellbio.utmb.edu/cellbio/cilia.htm)

Cilia are usually about 10 μm long and can be classified as motile and non-motile cilia. Motile cilia are capable of beating in a constant fashion and can therefore be considered, from engineering prospective, as natural actuators. On the other hand, non-motile cilia do not beat but undergo deformations imposed by the surrounding environment. They behave as natural sensors.

Motile cilia, which are of particular interest for the aim of this paper, are often present in large number on the surface of cells and are capable of coordinating their motion thus beating at the unison in a synchronised way. The motion of cilia is generated by basal bodies, at the end of each cilium. The cilia motion is used to move surrounding fluid, small particles across and along the cellular tissue, or to propel the cell itself.

Cilia are present in most biological systems. For example, human epithelial surfaces are ciliated. Motile cilia are found in the Fallopian tubes or in the trachea and are also used in the vesicles of the brain to circulate the cerebrospinal fluid. Synchronous beating of cilia is often employed to move secretions or particles. Examples of non-motile cilia are the terminal fibers of olfactory neurons. In addition, in the human eye, the outer segments of the rod photoreceptor cells are connected to the respective cell bodies by means of specialized non-motile cilia.

2.2 Peristaltic movements

The following statement properly defines peristalsis (Oxford English Dictionary, 2002): *"the involuntary constriction and relaxation of the muscles of the intestine or another canal, creating wave-like movements which push the contents of the canal forward"* [2]. Used for different purposes, peristaltic movements can be found in different biological organisms. In humans, for example, oesophagus, stomach and intestine perform peristaltic involuntary movements enabled by the muscles integrated in their side-walls. Peristalsis is based on an induced travelling wave of muscle contraction; cyclically muscle contractions make it possible to transport particles (food) throughout the digestive tube. Peristalsis can be also found in ureters, oviducts and other tube-like organs.

Another use of peristalsis, which is adopted by different animals, is locomotion. Earthworms cyclically contract their circular and longitudinal body muscles for moving forward. This motion has inspired systems currently available in the market, as inchworm piezoelectric linear actuators [3].

3 Potential Space applications of Distributed Actuation Systems

In the framework of this project we are interested to thin layers with embedded distributed actuators used to move surrounding particles and debris. There are several potential applications in space field. In the following paragraphs, we propose some concepts that are still in an embryonal phase, related to possible futuristic space applications.

3.1 Active compliant end-effectors

Picking up and manipulating planetary samples is a difficult task that is currently manly accomplished using rigid mechanisms and grippers. The performance of a robotic end-effector in terms of mass and volume saving and in terms of capability to gather planetary samples could be increased with the use of a distributed actuated sleeve. In fact, such a sleeve by acting as a trunk and being capable to perform peristaltic movements could be, in principle, quite miniaturized and highly dexterous.

3.2 Transport line for digging moles

One of the possible show stoppers for robotic moles aimed at digging for several meters into the soil is the transport line that should convey particles on the top of the planetary surface from underground [4]. The solutions which are often proposed consist of a series of pulleys conveying twisted wires. This solution, which require the use of motors and mechanisms placed on the top of the surface, seems to be quite bulky and volume inefficient.

The possibility to deploy a flexible tube which adheres to the surface of the dug hole and which is capable to convey particles using distributed actuators from the surface (see [4]) could be an interesting concept for far future transport lines.

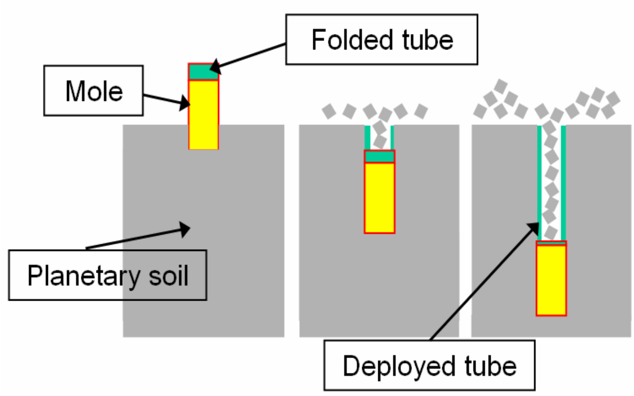

Fig. 2 Concept idea of transport line based on foldable tube having embedded distributed and redundant actuators

3.3 Fluidic distributed pump

Another possible futuristic application of actuators integrated on tubes and surfaces is represented by active transport of fluids. Particular natural distributed actuators, e.g. cilia, have evolved to operate on aqueous solutions and seem therefore suitable for inspiring the design of peculiar systems for fluid transport.

A pumping apparatus distributed along parts of fluidic systems could be considered, as advanced concept, for making circulate fluid in manned space vehicles or for pumping refrigerating fluid in far future telecommunication satellites.

3.4 Delivery sample systems based on DA surfaces

Delivery sample systems used for transporting samples gathered from the soil in exploration missions are made of a multitude of mechanisms that synchronously work together. The malfunctioning of one of the mechanisms results in a failure of the delivery sample system, thus preventing the analysis in loco of planetary samples (failure of a considerable part of the scientific mission). Space engineers are looking for systems suitable to adapt themselves for unforeseen circumstances, that are compact, highly redundant, and that allow fine positioning of the samples.

Using redundant actuators distributed and embedded on a surface (a concept idea of self actuated surface is presented in [5, 6]) could conceptually lead to a mass and volume save while improving the performance of novel delivery sample systems.

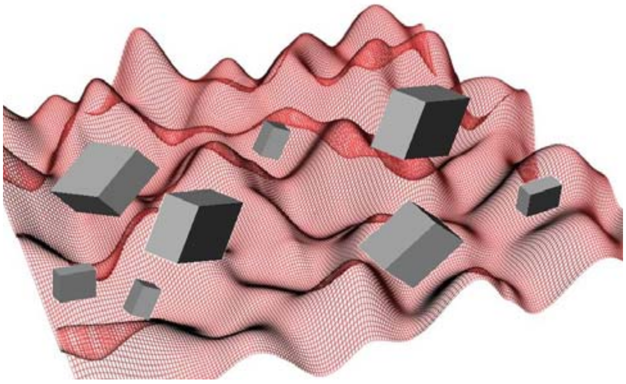

Fig. 3 Concept idea of flat surface with distributed actuators used to transport particles

3.5 Auxiliary locomotion systems

Locomotion in harsh terrains as those found in space scenarios is a compelling issue to be addressed by space engineers. Looking at nature could lead to novel solutions never envisioned before. In this framework, locomotion capability might be improved by surface equipped with a multitude of redundant miniaturized actuators that get in contact with planetary surfaces. Preliminary examples of distributed systems based on piezoelectric materials are already subject to intense research and investigation especially for moving autonomous micro-tool carriers for industrial use [4].

4 EAPs as emerging new actuation technologies

It is well recognized today that certain classes of polymers have concrete potentials as a possible answer to the demanding search for new actuation materials with appropriate properties. In particular, eligible polymers are those suitable for actuators of electromechanical type, i.e. steerable by electrical stimuli. Polymers capable of changing shape and/or dimensions in response to an electrical input are the so-called ElectroActive Polymers (EAPs) [7,8]. Materials belonging to this family usually show interesting intrinsic properties, such as sizeable active strains and/or stresses, large compliance, low density, ease of processing, low power consumption and low costs. Many of them have been known since many decades but have found a limited number of applications, despite their potentials, mainly because of their scarce development towards mature technological levels. Differently, promising recent results in material science, material processing and device design for such polymers are encouraging today the concentration of efforts for a concrete exploitation of the performance offered by many of them [9].

Electroactive polymers can be classified in two major categories: ionic EAPs (actuated by a transport of ions and molecules) and electronic EAPs (activated by an electric field) [7, 8].Table 1 summarizes such a classification, presenting the types of materials belonging to both groups.

Table 1 Classification of electroactive polymers

EAP type	Mechanism of activation	Materials
Ionic	Mass/ion transport	Conducting polymers Polyelectrolyte gels Ionic polymer-metal composites Carbon nanotubes
Electronic	Electric field	Dielectric elastomers Piezoelectric polymers Electrostrictive polymers Liquid crystal elastomers

Despite the very low driving voltages (order of 1 V) advantageously required by ionic EAPs, they typically present higher response times along with lower stability, lower reliability and lower durability with respect to those of electronic EAPs. Nevertheless, the latter pay superior performances with the need of considerably higher voltages (electric fields of the order of 10-100 V/µm are typically necessary).

Beyond the specific quantification, for each category of material, of fundamental figures of merit for actuation (subjected to a continuous improvement by ongoing research), some general features can be qualitatively highlighted, as reported in Table 2.

From a comparison of the actuating performances it can be easily deduced how the attractive properties of dielectric elastomers are responsible of the growing tendency to view them as one of the most promising classes of polymer materials for many actuation tasks. Such a superiority of rubbery insulators has driven their selection as candidates for this study.

Table 2 Qualitative comparison of fundamental actuation properties of EAPs (legend: h=high, m=medium, l=low)

Material	Strain	Stress	Voltage	Response times	Reliability, Lifetime
Conducting polymers	L/M	H	L	H	L
Polyelectr. gels	H	L	L	H	L
Ionic polymer-metal comp.	H	L	L	H	L
Carbon nanotubes	L	H	L	H	L
Dielectric elastomers	H	M	H	L	H
Piezoelectr. polymers	L	H	H	L	H
Electrostr. polymers	L	H	H	L	H
Liquid crystal elastomers	L	--	H	L	--

This technology relies on the use of insulating rubbery polymers with a low elastic modulus. They can exhibit large deformations in response to high electric fields. In particular, when a thin film of dielectric elastomer is sandwiched between two compliant electrodes and a high voltage difference is applied between them, the polymer undergoes a thickness squeezing and a surface expansion. Such a deformation mainly arises from a Coulombian effect, due to the electrostatic interactions among free charges on the electrodes [10]. Acrylic and silicone elastomers are the most representative materials of this class of EAPs. Such kinds of polymers can be very compliant and some of them have shown the highest reported actuating deformations among all electroactive polymers. In particular, thickness strains up to 60-70% at 400 V/µm, area strains up to 200% at 200 V/µm and corresponding stresses of some MPa have been reported [10].

Silicone made elastomers, such as the poly(dimethylsiloxane) family, are particularly attractive due to their ease of processing, suitable mechanical and electrical properties and typical low costs. Moreover, some representatives can suit strict space environmental constraints. With this regard, it is known that certain silicone rubbers can withstand exceptionally broad temperature ranges with minor degradation of electromechanical actuation performances. In particular, silicone based actuators have been successfully tested between -100 and +200 °C [11]. Moreover, several tests on different types of silicones to be used for actuation are currently in progress within a specific ESA project ('EAP actuators').

5 Space Applications of EAPs

A space system partially equipped with EAP based actuation technologies can be expected to gain several advantages, as those hereinafter mentioned. First of all, the intrinsic actuation properties of materials would permit to reduce the number of moving parts devoted to transfer motion and forces to loads, therefore reducing complexity and costs of the system and potentially increasing its reliability. Secondly, the low mass and small size of polymer-made devices may enable a useful reduction of weights and volumes. Moreover, the large material compliance could be exploited for a 'packaging' of devices and sub-systems in small volumes for transportation. These and other features have encouraged, since a few years, the promotion of the first studies on space applications of EAPs.

JPL (Jet Propulsion Laboratory, NASA, U.S.A.) has investigated the use of an actuator made of an ionic polymer-metal composite as a dust wiper for camera lenses of a space rover [7,12]. A prototype of the device, which was conceived for the MUSES-CN's Nanorover and tested on ground facilities, was able to provide a bending of the wiper of about ±90 degrees with an input voltage signal of 1-3 V at about 0.3 Hz [13].

The first studies for space applications of dielectric elastomer actuators are emerging nowadays. One of the most significant of them concerns the shape control of lightweight space mirrors. Considered solutions employ laminated or inflatable reflective structures with integrated actuation elements or segmented rigid mirrors driven by external linear actuators [11].

ESA is investing efforts in this field as well, with both the project 'EAP actuators' (currently in course) and two 'Ariadna' initiatives of the Advanced Concepts Team (Ariadna studies): 'EAP-based artificial muscles as an alternative to space mechanisms' [14] and 'Bio-inspired distributed system for particles transport'. The latter initiative has been the framework for the research activities discussed in this paper.

6 Promising possible implementations

Considering the identified space applications and the inherent properties of dielectric EAPs, the authors focused their attention on novel engineering distributed systems inspired by peristalsis. Three promising concept ideas, which take into account technology readiness (concepts proposed are based on the use of actuators developed by the Research Centre 'E. Piaggio' of the University of Pisa), are presented and discussed in the following paragraphs.

6.1 First concept

In the first concept, a travelling wave on a polymeric surface is induced by sequentially actuating micro-discrete EAPs elements as shown in Fig. 4.

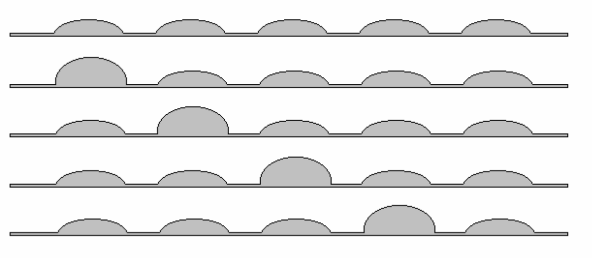

Fig. 4 Concept for a transport system with distributed actuation based on buckling actuators.

This concept can be implemented by taking advantage of the so-called '*buckling dielectric elastomer actuators'* [15]. They consist of an elastomer membrane whose curvature can be modulated with an applied electric field. Such an effect can be achieved by exploiting the operation principle of dielectric elastomer actuators, in combination with particular boundary conditions, as represented in Fig. 5. The membrane can change its curvature from a rest (a) to an activated (b) status. A pre-deformation of the membrane permit its buckling when a high voltage is applied between the electrodes (Fig. 5 b).

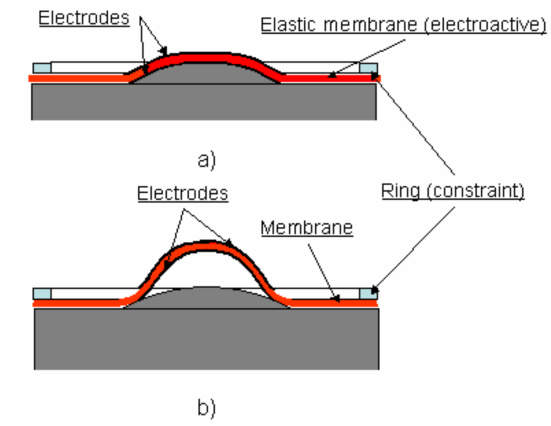

Fig. 5 Schematic drawing of the cross-section of a buckling dielectric elastomer actuator.

Prototypes of this actuator embedding also a piezoresistive strain sensor have been developed. Fig. 6 shows a plot of preliminary performances.

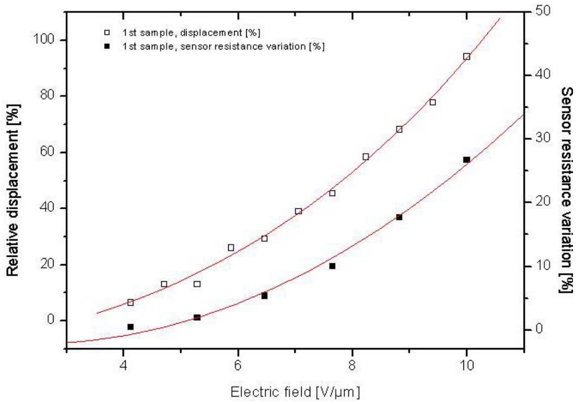

Fig. 6. Electric field dependence of both the relative displacement of the membrane upper point and the sensor resistance

6.2 Second concept

In this case, the concept proposed consists of a tubular structure made of a sequence of contractile/expanding artificial muscle modules that are sequentially activated as shown in Fig. 7. Such a solution would mimic the muscular peristalsis of the biological digestive apparatus.

A preliminary implementation of this concept can be obtained by using '*helical dielectric elastomer actuators'* [16]. They are contractile linear actuators made of two helical compliant electrodes interposed to two elastomeric insulators.

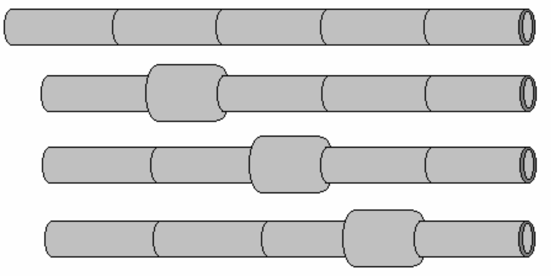

Fig. 7. Concept for a transport system with distributed actuation based on helical actuators.

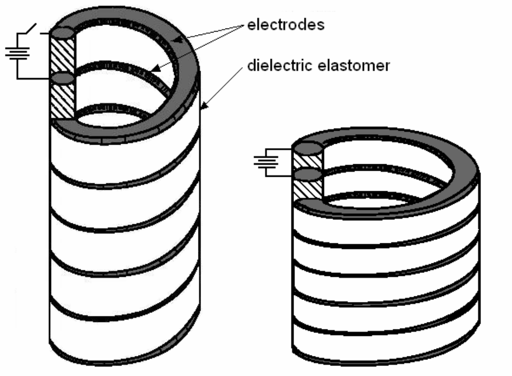

Fig. 8 Schematic drawing of a helical dielectric elastomer actuator.

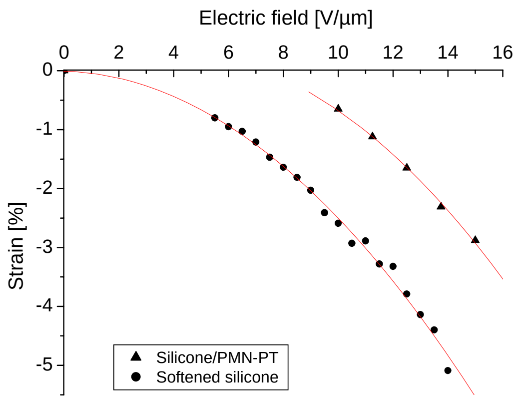

Fig. 9 Contraction strain vs applied electric field for prototype helical actuators.

Accordingly, the device consists of a hollow cylinder of dielectric elastomer, having two helical compliant electrodes integrated within its wall (Fig. 8). By applying a high voltage difference between them, the attractions among opposite charges cause the axial contraction of the actuator, as well as related radial expansions (Fig. 8). Fig. 9 presents preliminary data obtained by prototype samples of this actuator.

6.3 Third concept

A third potential concept consists of multiple arrays of micro-linear actuators that can be used to assemble a transport system sketched in Fig. 10.

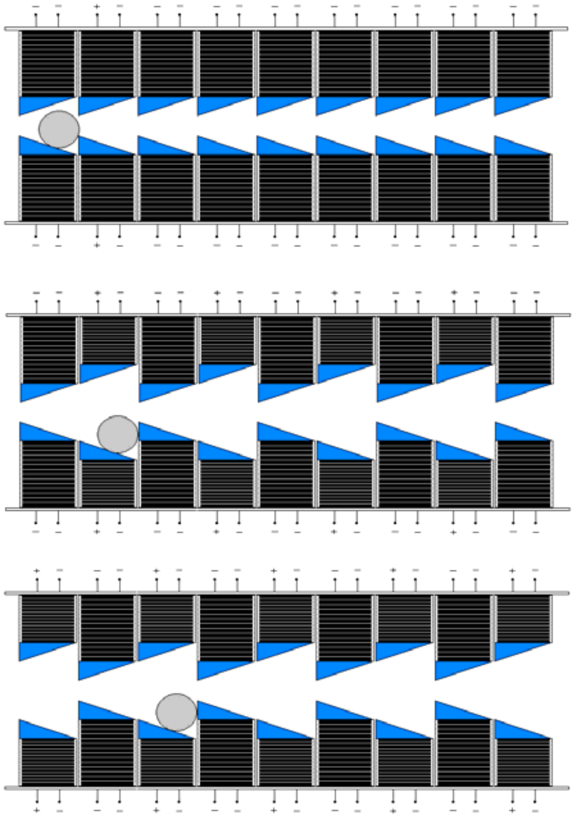

Fig. 10 Concept for a transport system with distributed actuation based on folded actuators.

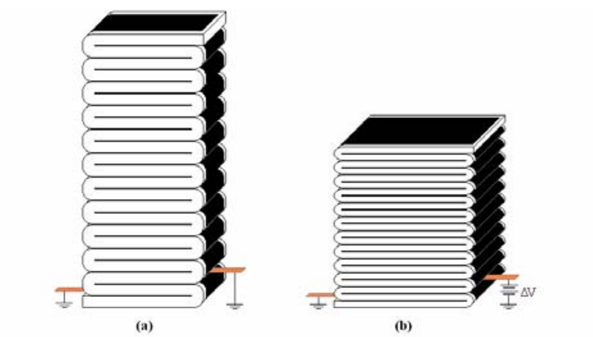

Fig. 11 Schematic drawing of a folded dielectric elastomer actuator.

This concept can be implemented by using an array of '*folded dielectric elastomer actuators'* [17]. They are contractile linear actuators consisting of a strip of electroded elastomer which is folded up, as shown in Fig. 11a. By applying a high voltage difference between the electrodes, a contraction of the device is achieved (Fig. 11b).

Experimental contraction strains for prototype samples are shown in Fig. 12.

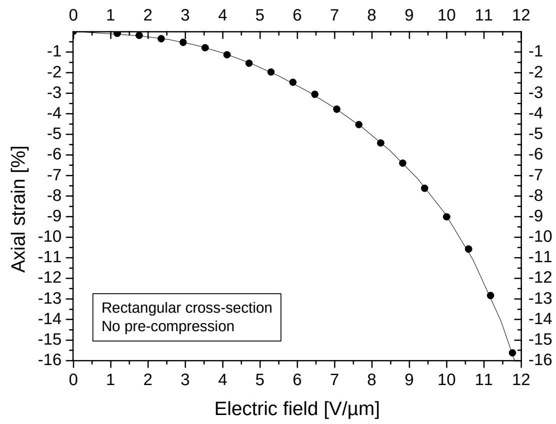

Fig. 12 Axial strain vs applied field for a prototype folded actuator.

7 Future directions

The three concepts mentioned above are currently under deep investigation. Further solutions, aimed at minimizing the size and volumes of the actuation components, are also being considered. Future directions concern firstly a thorough analysis of the proposed concept designs using non-linear models to predict the performance of the system. Secondly a prototyping phase, aimed at integrating the EAPs modules, is needed as it allows a validation of the above mentioned analysis. The third step concerns the development phase of the system in order to improve reliability, robustness, and process repeatability. In the authors' opinion, these three phases are of straightforward implementation as the concept designs presented in this paper have being conceived while assessing the readiness level of the proposed technology.

8 Conclusions

This paper presents results obtained in the assessment of novel bio-inspired concepts analysed in order to develop new distributed actuation systems potentially suitable for space applications. Such systems are conceived considering the use of electroactive polymers as these new materials show interesting actuation performances. In particular, two natural distributed actuated systems are investigated, five futuristic possible space scenarios are identified and three novel bio-inspired concepts are proposed.

Acknowledgments

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