Bio-inspired distributed system for thermal (or particles) transport

Final Report

Authors: Federico Carpi, Danilo De Rossi

Affiliation: University of Pisa, Interdepartmental Research Center "E. Piaggio"

ESA Research Fellow/Technical Officer: Carlo Menon

Contacts:

Federico Carpi
Tel: +39 050 2217064
Fax: +39 050 2217051
e-mail: f.carpi@ing.unipi.it

Carlo Menon
Tel: +31 (0) 71 56 58675
Fax: +31(0)715658018
e-mail: act@esa.int

Available on the ACT website
http://www.esa.int/act

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Executive Summary

This document represents the final report of the study "*Bio-inspired distributed system for thermal (or particles) transport*" performed by the Interdepartmental Research Centre "E. Piaggio" of the University of Pisa within the framework of the ARIADNA activities promoted by the European Space Agency (ESA). According to a specific request of ESA, this study has been focused on systems for transport of particles only. The main goal of the study was to conceive possible new solutions, inspired by natural systems, for structures embedding distributed actuators for transport of small and lightweight particles, to be used for possible space operations. Some preferred concepts for possible designs of new distributed transport systems were proposed. They were inspired by peristalsis-like motions and consist of distributed actuating structures made of one specific category of electroactive polymers, namely dielectric elastomers. One of the considered solutions was selected among the others, according to its relatively superior simplicity. Prototype samples of a scaled model of an elementary actuation unit suitable for assembling the candidate system were fabricated. Each unit consists of a silicone-made cylindrical hollow dielectric elastomer actuator, working in radial mode. Actuation properties of such units were preliminarily investigated, by performing elementary electromechanical bench tests.

The contents of the report are organized as follows. The Introduction presents the motivation behind the activities performed in this study; in particular, possible space applications of new distributed actuation systems are briefly presented. Aimed at taking inspiration from natural solutions for distributed actuation, a brief remind about the most common natural examples of this kind is reported. The third part of the report presents a selection of the most promising materials for new concepts and describes possible concepts for new distributed transport systems. Among them, the selected candidate system is then described in greater details. The following part presents prototype samples of a scaled model of an elementary actuation unit and describes the testing technique. Test results are then reported. A review of technologies suitable for distributed actuation systems is included as an Appendix.

Keywords: Bio-inspired, distributed, particles transport, motile cilia, peristalsis, peristaltic, electroactive polymer, EAP, dielectric elastomer, polymer actuator, cylindrical, digging system.

1 Introduction

Space technology is usually very conservative: reliability and robustness are, necessarily, its main drivers. Space systems have to trust on consolidated technologies capable of offering 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. In particular, novel concepts coming from research activities are the lymph for possible developments of successful and competitive new solutions for space system, as for any other field of technology. In this respect, this study was focused on the definition of possible solutions for new generations of space systems to be used for transports of small and lightweight particles. A search for new solutions in this area mainly arises from the necessity of reducing the complexity, the weight and the dimensions of state-of-the-art systems.
Surface-distributed actuations might confer particles transport properties to structures. As an example, flexible tubes integrating actuating elements in their wall may enable transports of particles from one point to another, by exploiting, for instance, either dimensional variations of the tube or beatings of elements embedded on a surface (Fig. 1).

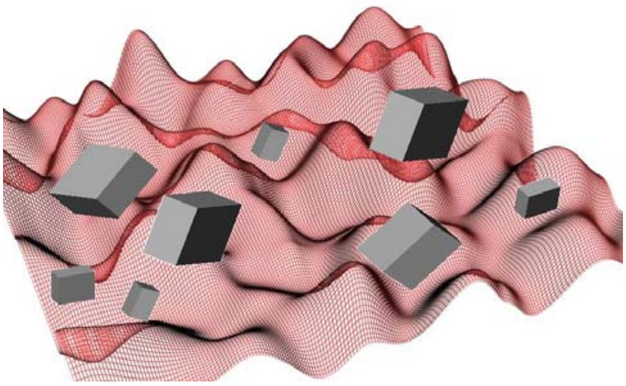

Fig. 1: Concept of a flat surface with distributed actuators to be used for particles transport.

As an example, a concept idea for self-actuated surfaces is presented in [5, 6].
Some specific potential applications that may benefit from new distributed actuation systems can be identified, as described below.

Active compliant end-effectors represent one of the possible application domains. Picking up and manipulating planetary samples is a difficult task, that is currently manly accomplished by using rigid mechanisms and grippers. The performance of a robotic end-effector in terms of mass and volume saving and in terms of capability of gathering planetary samples could be increased with the use of distributed actuated sleeves. Sleeves capable of performing peristaltic movements could be, in principle, quite miniaturized and may result highly dexterous.

Transport line for digging moles is another application of interest. 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 most commonly used solution consists of a series of pulleys conveying twisted wires. This solution, which requires the use of motors and mechanisms placed on the top of the surface, seems to be quite bulky and volume inefficient. As an alternative, the possibility of deploying a flexible tube adherent to the surface of the dug hole and capable of conveying particles by means of distributed actuators from the surface ([4]) could be an interesting concept for far future transport lines (Fig. 2).

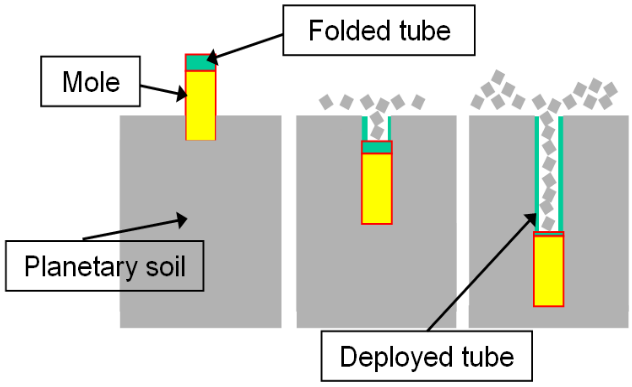

Fig. 2: Concept idea of transport line based on foldable tube having embedded distributed and redundant actuators

Active transport of fluids represents another possible application of actuators integrated in tubes and surfaces. As an example, a pumping apparatus distributed along parts of fluidic systems could enable more efficient circulations of fluids in manned space vehicles or in refrigeration systems for satellites.

Delivery sample systems represent another field of possible use. They are employed for transporting samples gathered from the soil in exploration missions. They are currently made of a multitude of mechanisms that synchronously work together. The malfunctioning of one of the mechanisms results in a failure of sample delivery, thus preventing an in-loco analysis of planetary samples. As an example, this can be a considerable source of failure for scientific missions.

In order to conceive and design new solutions capable of satisfying such types of needs, the natural world may provide a valuable source of inspiration. In fact, millions years of evolution have enabled the progressive development of efficient systems for particles transport, by adopting distributed sets of actuating structures. Such distributed elements cover large portions of different kinds of biological surfaces in humans, animals and plants. In particular, this concept has been developed by nature in several ways. As an example, ciliated cells and peristalsis of muscles certainly are two emblematic representatives of natural distributed systems of actuation. Motile cilia are employed, for instance, in the respiratory tract to move secretions or particles, in the uterus and Fallopian tubes to propel the ovum from the ovary to the uterus, or in the vesicles of the brain to circulate the cerebrospinal fluid. Peristaltic movements of muscles, instead, are used in the oesophagus, the stomach and the intestine to transport the food through the digestive tract; moreover, they are exploited by several animals for locomotion as well, as in the case of earthworms.

A brief remind about both these types of biological distributed systems is given in the following section, so as to provide a first and preliminary evidence about their potential capability of inspiring the design of new concepts for particles transport systems.

2 Biological concepts for distributed actuation

Animals and plants have a wide variety of actuators customized for particular purposes and uses. Many of them show actuating elements that are 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 the structures in which they are located.

In order to provide just a brief remind about this vast field, it is worth mentioning here at least the examples reported below, related to distributed biological actuations in the form of motile cilia and muscular peristalsis.

2.1 Natural motile cilia

Cilia are a whole of microscopic hair-like structures (each one called *cilium*), extending from plasma membrane of several types of cells, as shown in Fig. 3.


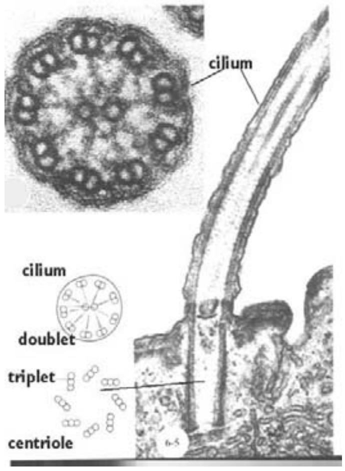

Fig. 3: Left: some cilia. Right: cross- and longitudinal- section of a cilium (from [1]).

In particular, a cilium is an organelle (i.e. a structure with specialized function) projecting from eukaryotic cells. Cilia are extensions of the cell plasma membrane and contain an array of parallel microtubules (collectively called *axoneme*), running longitudinally through the entire organelle. Microtubules have a typical spatial arrangement, consisting of nine peripheral doublets of microtubules and two central single microtubules (organization called "9+2"), as shown in the cross section of Fig. 3.

Cilia have lengths usually of the order of 10 µm. Two types of cilia can be distinguished: *motile cilia* and *non-motile cilia*. The first type consists of structures capable of a constant beat, while those of the second type do not beat, usually working as sensors.

Motile cilia are organized structures usually being present on a cell's surface in large numbers and being capable of rhythmic and coordinated motions. In fact, each cilium is able to beat acting in unison with other neighbouring cilia. Their beating is usually exploited to provide motion either to their own cells, or to surrounding fluids over their cells' surface, or to small particles across or along the cellular tissue.

The movement and the direction of these cilia is controlled by basal bodies located in proximity of the cellular end of each cilium. Microtubule sliding related to the movement of each cilium is powered ATP, which is generated by mitochondria that are found near the basal body.

Cilia are found in all animals. As an example, protozoic ciliates use motile cilia for locomotion or to move liquid over their surface. In humans, several epithelial surfaces of the body are ciliated (e.g. ciliated columnar epithelium), as depicted in Fig. 4.

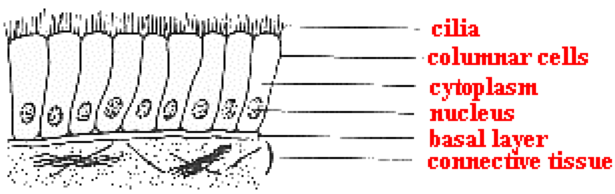

Fig. 4: Drawing of a ciliated epithelial surface.

The synchronous and rhythmic beating of these cilia in a certain direction is usually employed to move secretions or particles. Motile cilia are found, for instance, in the respiratory tract (trachea), where they sweep mucus and dirt out of the lungs by means of a gradual movement along the surface of the respiratory epithelium. They are present also in the uterus and Fallopian tubes of females, where their beating propels the ovum from the ovary to the uterus. As another example, cilia in the vesicles of the brain circulate the cerebrospinal fluid.

In contrast to the motile cilia, non-motile cilia usually occur as a one cilium per cell. As an example, 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. Likewise, the terminal fibers of olfactory neurons are non-motile cilia, where odorant receptors are located.

2.2 Muscular peristalsis

Peristalsis is a process of wave-like successive muscular contractions employed by humans and animals to perform different actions.

In humans, the large and hollow organs of the digestive system contain muscles that enable their walls to move. The peristalsis of the oesophagus, stomach and intestine is an involuntary movement of the muscles located in the walls of these organs, which permits to transport the food through the digestive tract. It consents to propel food and liquids and also to mix them. Peristalsis induces a wave of contraction which travels through the muscles. In particular, the muscle of a hollow organ produces repeatedly its local narrowing, followed by a new widening, so that to propel the narrowed portion along the length of the organ. Such contraction waves are able to push food and fluids in front of them through the organ (Fig. 5).

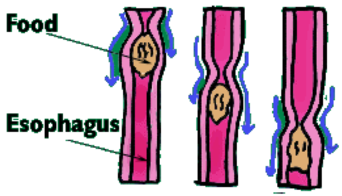

Fig. 5: Drawing of the peristalsis of an esophagus.

In addition to the digestive system, peristalsis is also used in oviducts, ureters and other tube-like organs.

In contrast with such a use of peristalsis, several animals adopt it for different purposes, such as locomotion. For instance, this is the case of earthworms. These animals implement forward motions by exploiting the alternating contraction of longitudinal and circular muscles of the numerous segments which constitute their body, as sketched in Fig. 6.

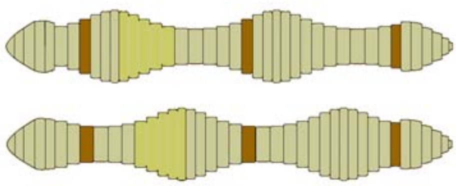

Fig. 6: Drawing of the peristaltic motion of an earthworm.

Series of contractions periodically repeated permit the generation of a longitudinal wave, which sequentially compresses and releases each segment. This mechanism provides longitudinal motion to the animal, as depicted in Fig. 7.

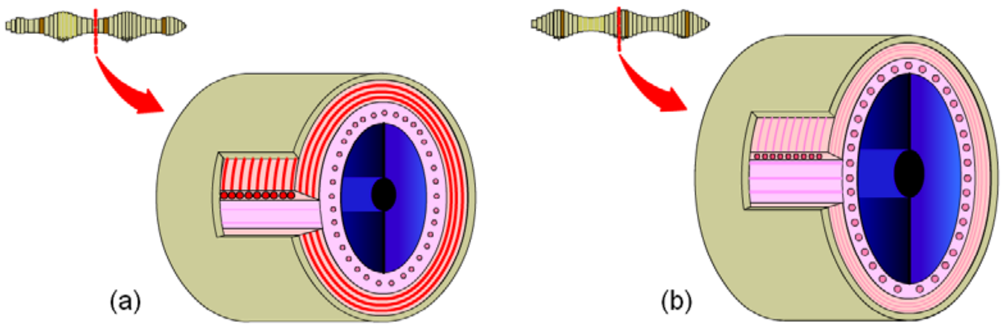

Fig. 7: Schematic contraction of each segment of an earthworm during its peristaltic locomotion.

This type of motion has inspired systems currently available in the market, as inchworm piezoelectric linear actuators [3].

3 EAPs as emerging actuation materials

In order to identify the most suitable type of material and technology to be studied for the implementation of new bio-inspired solutions for distributed actuation, several candidate representatives were reviewed. The Appendix of this report presents a concise survey of the current state of the art.

As a result of such an evaluation, electroactive polymers (EAPs) were selected as particularly attractive materials. The use of electroactive polymers as intelligent materials for actuation was spread out some years ago by the need for several technical domains of new actuation solutions, capable of bypassing the inadequacy of traditional motor technologies in many specific applications. In particular, aimed at the satisfaction of new demanding needs for actuation, such as large deformations, high compliance, high efficiency and high power-to-weight and power-to-volume ratios, arising from the exploration of new scientific and technological frontiers, in recent years new types of actuators have been proposed. They are based on electroactive polymers. They consist of materials capable of changing dimensions and/or shape in response to opportune electrical stimuli [7,8]. These polymers show interesting properties, such as sizable active strains and/or stresses, high compliance, low specific gravity, high grade of processability and, in most cases, low costs. Although many of them have been known since many decades, they have found very limited applications, despite their potentials, due to a scarce technical development. This trend is changing in the last years, as a consequence of a higher concentration of efforts for concrete exploitations [9].

EAP materials are classified in two major categories: ionic EAPs, activated by an electrically-induced transport of ions or molecules, and electronic EAP, activated by an external electric field and by Coulombian forces [7, 8]. Table 1 summarizes this classification, listing for both types of EAPs the most representative materials.

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.

Table 2: Qualitative comparison of fundamental actuation properties of EAPs (legend: H=high, M=medium, L=low)

Material	Strain	Stress	Voltage	Response time	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	--

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

4 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 the the project '*EAP actuators*' (currently in course), the ITI project '*Contractile linear actuator and sensor based on dielectric elastomers*' (2007) and two ARIADNA initiatives of the Advanced Concepts Team (Ariadna studies): '*EAP-based artificial muscles as an alternative to space mechanisms*' [14] and the present study.

5 Selected material and technology: dielectric elastomer actuators

Dielectric elastomer actuators rely 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 regard to this, certain space-grade 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 environmental tests on different types of silicones to be used as possible materials for space applications have been performed within the ESA project '*EAP actuators*'.

According to such properties of this specific class of EAPs, interesting concepts may derive from the study of bio-inspired distributed actuators based on dielectric elastomers. For this reason, possible solutions based on such an approach have been specifically conceived in this study, by adopting actuating configurations recently developed by this Research Center. They are described in the next section.

6 Candidate concepts for bio-inspired distributed systems for particles transport

In order to conceive new bioinspired solutions for distributed actuation, the attention was focused on possible systems inspired by natural peristalsis. Four concept ideas are presented and discussed in the following.

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. 8.

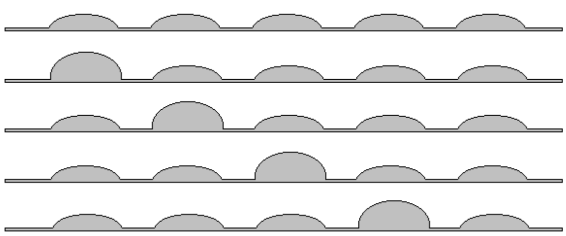

Fig. 8: Concept for a transport system with distributed actuation based on buckling actuators.

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. 9:. The membrane can change its curvature from a rest (a) to an activated (b) status. A pre-deformation of the membrane permits its buckling when a high voltage is applied between the electrodes (Fig. 9:b).

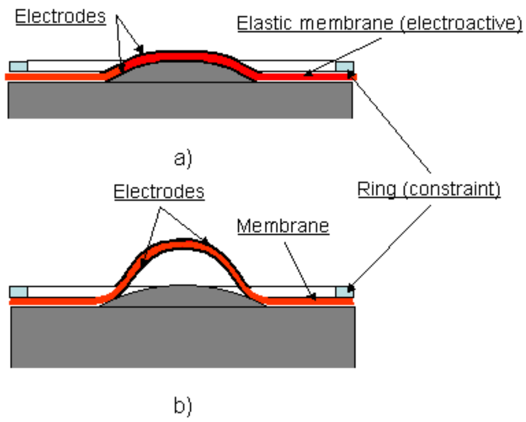

Fig. 9: Schematic drawing of the cross-section of a buckling dielectric elastomer actuator.

Prototypes of this actuator embedding also a piezoresistive strain sensor have been developed. Fig. 10 shows a plot of preliminary performances.

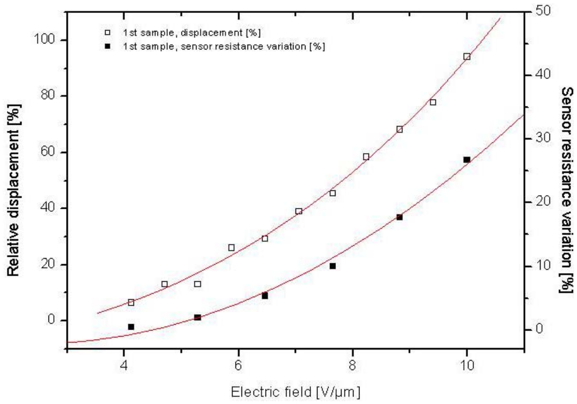

Fig. 10: Electric field dependence of both the relative displacement of the membrane upper point and the sensor resistance.

6.2 Second concept

In this case, the concept proposed consists of a tubular structure made of a series of axially-contracting and radially-expanding modules that are sequentially activated as shown in Fig. 11. Such a solution would mimic the muscular peristalsis of the biological digestive apparatus.

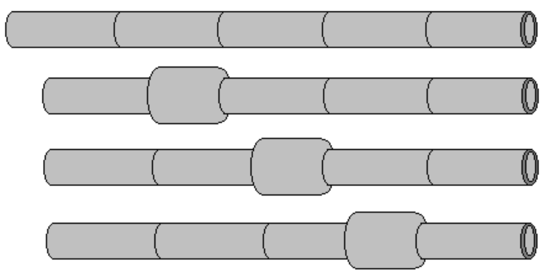

Fig. 11: Concept for a transport system with distributed actuation based on helical actuators.

An 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. Accordingly, the device consists of a hollow cylinder of dielectric elastomer, having two helical compliant electrodes integrated within its wall (Fig. 12:). 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. 12:). Fig. ***13:***13 presents preliminary data obtained by prototype samples of this actuator.

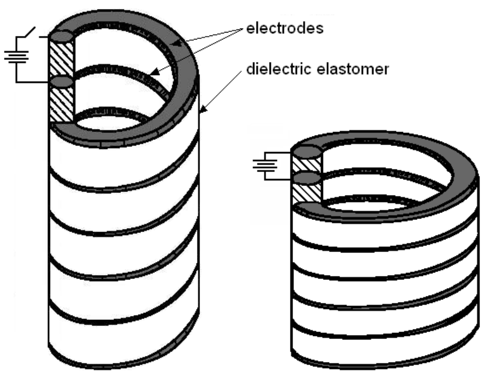

Fig. 12: Schematic drawing of a helical dielectric elastomer actuator (from [16]).

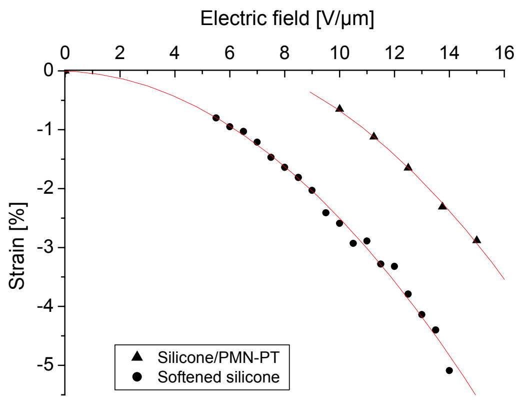

Fig. 13: Contraction strain vs applied electric field for prototype helical actuators (from [16]).

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. 14.

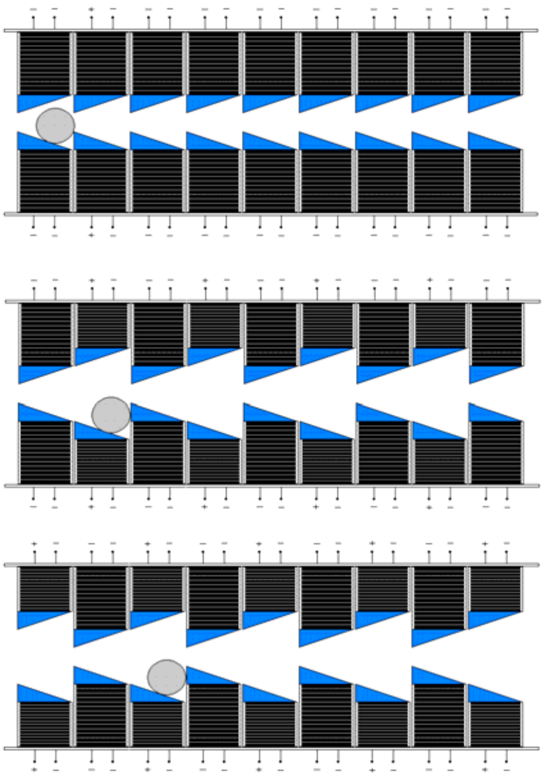

Fig. 14: Concept for a transport system with distributed actuation based on folded actuators.

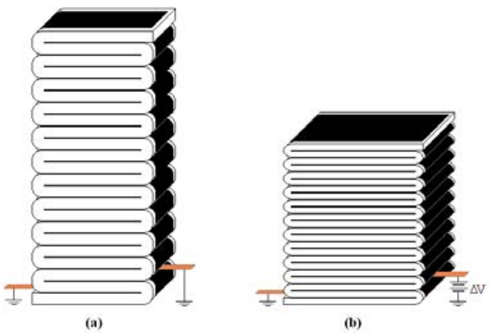

Fig. 15: Schematic drawing of a folded dielectric elastomer actuator (from [17]).

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. 15:. By applying a high voltage difference between the electrodes, a contraction of the device is achieved (Fig. 15:). Experimental contraction strains for prototype samples are shown in Fig. 16.

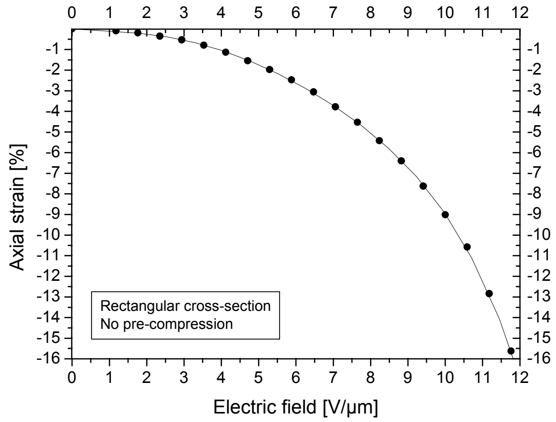

Fig. 16: Axial strain vs applied field for a prototype folded actuator (from [17]).

6.4 Fourth concept

The last concept taken into consideration is substantially analogous to the second concept. However, it uses a different type of unit. In fact, in this case the tubular structure is made of a series of radially-expanding modules whose length does not vary; this is made possible by adopting specific constraints. In particular, the structure adopts ‘*cylindrical dielectric elastomer actuators’* [18]. They are linear actuators made of a hollow tube of elastomer coated with internal and external compliant electrodes (Fig. 12:). Nevertheless, this type of unit can not be employed as it is. In fact, by applying a high voltage difference between the electrodes of a cylindrical actuator, the attractions among opposite charges squeeze the tube wall and produce a radial expansion and an axial elongation (Fig. 12:7).

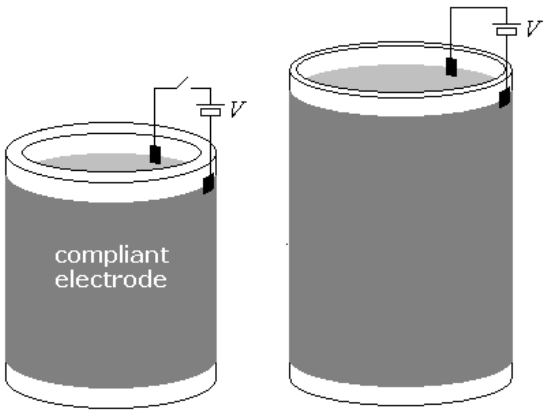

Fig. 17: Schematic drawing of a cylindrical dielectric elastomer actuator (from [18]).

As an example, Fig. ***13:***18 presents preliminary data obtained by prototype samples of this actuator.

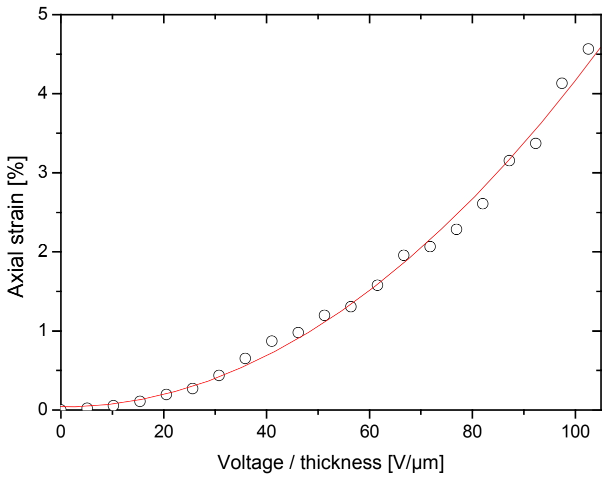

Fig. 18: Contraction strain vs applied electric field for a prototype cylindrical actuator (from [18]).

The elongation of the tube would be a disadvantage, since it is antagonist to the radial expansion. On the contrary, a maximization of the radial effect is preferable, in order to maximize the 'pumping' efficacy of the tubular structure. Accordingly, a specific constraint was introduced, in order to impede the axial elongation. Such an effect can be obtained by using inextensible auxiliary components, such as simple wires (see the next section).

7 Selected concept and experimental investigations

The fourth solution described above was selected as the most viable. In fact, according to the relatively higher simplicity of the actuation unit and higher readiness of the necessary actuation technology, this concept appeared particularly attractive.

A possible driving scheme for a sequential activation of the single actuating units is shown in Fig. 19.

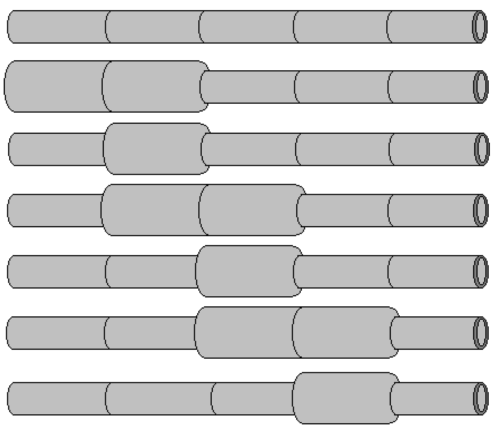

Fig. 19: Sequential activation of the actuating units.

This scheme foresees that two adjacent units are always active. In order to move particles along one single direction (from left to right in Fig. 19), firstly the unit behind is deactivated and then the unit ahead is activated. This procedure is repeated cyclically, so as to allow step-by-step transportations.

Prototype samples of a scaled model of an elementary cylindrical unit were fabricated. The considered unit consists of a cylindrical hollow tube made of a silicone rubbers. Samples were fabricated by using a soft commercial silicone (TC-5005 A/B-C, BJB Enterprises Inc., U.S.A.). It consists of a poly(dimethylsiloxane) mixture. According to previous investigations, this material enables high active strains at relatively low fields [17]. It consists of a three-component product, whose elastic modulus can be modulated by varying the amount of a plasticizer (softener). In order to obtain very soft samples, a 40 wt% of softener was used in this study. Following a degassing phase, the material was cured at room temperature for one day in planar moulds, so as to obtain flat samples with a typical thickness of about 0.9 mm. Cylindrical structures were obtained from the flat samples by arranging them with a closed cylindrical shape and sealing the extremities in contact. Compliant electrodes were made of a silicone/carbon-black mixture (CAF 4, Rhodorsil, France / Vulcan XC 72 R, Carbocrom, Italy). One of them was made by smearing the conductive mixture onto one side of the flat sample before the cylindrical shaping, while the second electrode was applied after the shaping and the sealing of the dielectric.

Fig. 20 shows an example of free stroke of an actuator sample.

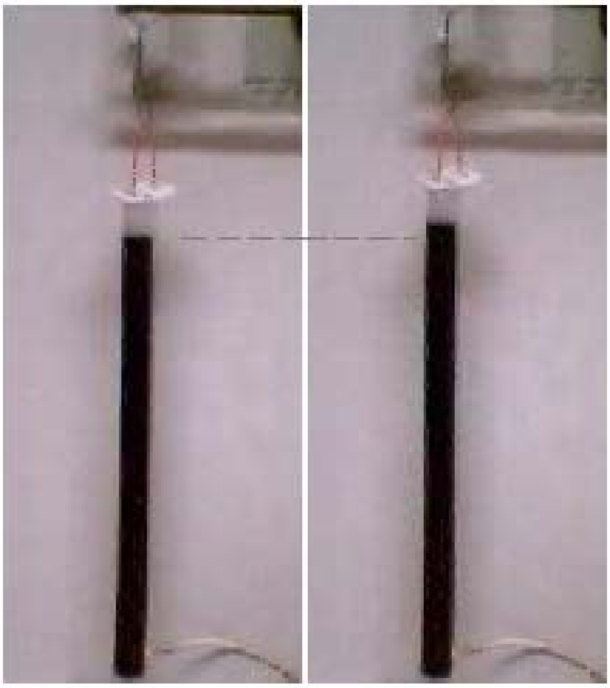

Fig. 20: Example of isotonic free stroke of a silicone-made cylindrical actuator.

According to previous studies about cylindrical dielectric elastomer actuators [18], the electromechanical transduction can be modelled by considering that the electrostatic internal and external pressures (Maxwell stresses) p_a and p_b due to an applied voltage V (Fig. 21) are given by the following expressions:

$$p_a = \frac{\varepsilon V^2}{2\ln^2\left(\frac{b}{a}\right)a^2 b(b^2-a^2)}\sqrt{a^6+b^6-a^2b^4-b^2a^4+8\ln\left(\frac{b}{a}\right)(b^2-a^2)a^2b^2+4\ln^2\left(\frac{b}{a}\right)(b^2+a^2)a^2b^2} \quad (1)$$

$$p_b = \frac{\varepsilon V^2}{2\ln^2\left(\frac{b}{a}\right)ab^2(b^2-a^2)}\sqrt{a^6+b^6-a^2b^4-b^2a^4+8\ln\left(\frac{b}{a}\right)(b^2-a^2)a^2b^2+4\ln^2\left(\frac{b}{a}\right)(b^2+a^2)a^2b^2} \quad (2)$$

where a and b are respectively the internal and external radii (Fig. 21) and $\varepsilon=\varepsilon_r\varepsilon_0$ is the absolute value of the elastomer dielectric constant, given by the product of the relative dielectric constant ε_r of the material and the dielectric permittivity ε_0 of vacuum (ε_0=8.85×10^{-12} F/m).

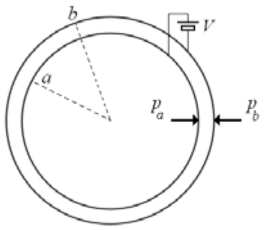

Fig. 21: Cross-section of a cylindrical actuator.

According to Eqs. (1) and (2) one can easily verify the equality of the electrostatic internal and external forces F_a and F_b that act on the lateral surfaces of the tube:

$$F_a=F_b \qquad (3)$$

In order to force the actuation along the radial direction only, a specific constraint imposing an isometric condition along the axial direction was introduced. For this purpose, the experimental set-up sketched in Fig. 22 was considered. Four flexible but inextensible wires were arranged outside the actuator, by connecting them to flat plastic supports fixed at the extremities of the actuator. The wires do not allow any elongation of the structure once it is electrically activated by a high voltage difference applied between the electrodes. This solution permits to maximize the radial expansion (Fig. 23).

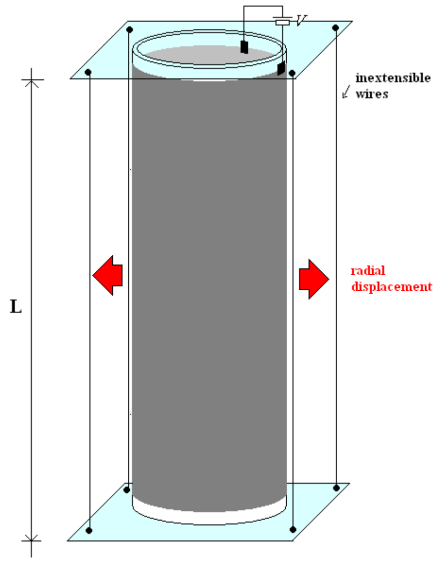

Fig. 22: Cylindrical actuator connected to external inextensible wires used to block active elongations.

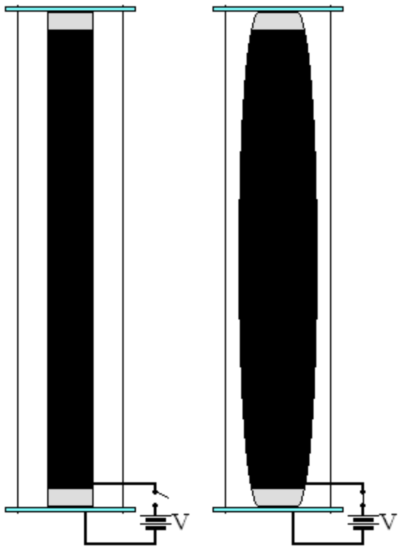

Fig. 23: Lateral view of an activation of a cylindrical actuator connected to external inextensible wires.

Actuation properties of such a type of unit were preliminarily investigated, by performing elementary electromechanical bench tests. Tables 3 and 4 list some basic material properties and geometrical parameters of tested samples.

Table 3: Material properties

Elastomer type	**Elastic modulus** Y **[kPa]**	**Poisson's ratio** ν	**Relative dielectric constant** ε_r	**Absolute dielectric constant** $\varepsilon=\varepsilon_r\varepsilon_0$ **[F/m]**
Silicone BJB TC5005	50	0.499	5	44.25×10^{-12}

Table 4: Geometrical parameters

Electrode length [mm]	**Actuator length [mm]**	**Internal radius [mm]**	**External radius [mm]**	**Thickness [mm]**
L = 163.0	L_{tot} = 174.0	a = 4.1	b = 5.0	b-a = 0.9

Electrically induced radial displacements of actuator samples were measured as follows. The actuator was arranged in vertical position, with its lower and higher ends constrained. Increasing step-wise high voltages were applied and for each voltage the steady-state radial expansion was detected by using an optical technique (video frames capturing and analysis). Voltages were increased up to the dielectric breakdown of the material. Fig. 24 shows pictures of the lateral actuation of a prototype sample.

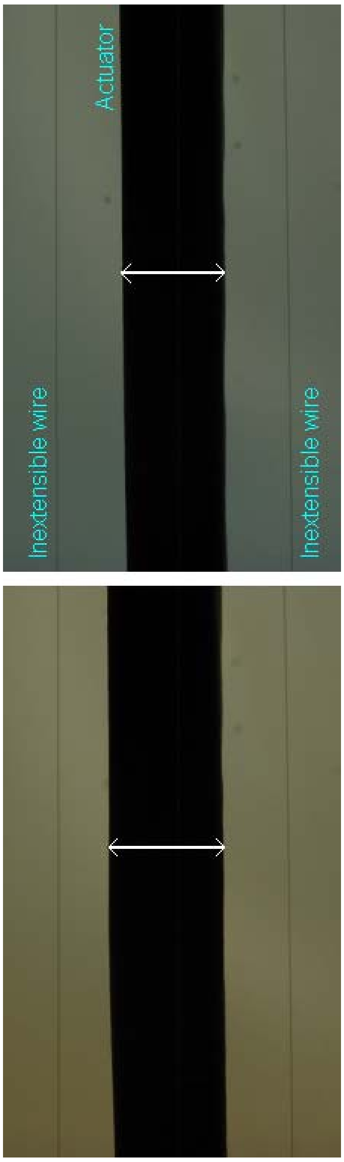

Fig. 24: Pictures of the central portion of a cylindrical actuator: (top) device at rest; (down) device with electrical activation.

For each applied voltage the relative radial expansion of the actuator was calculated as follows:

$$\text{Relative radial expansion} = \frac{2b_e - 2b}{2b} \quad (4)$$

where $2b_e$ is the electrically-induced external diameter.

Fig. 25 presents measured values of the relative radial expansion of the actuator for different values of voltage per unit wall-thickness. As an observation, it is worth stressing that voltage per unit thickness can not be regarded here as an electric field, even though they have the same dimensions. In fact, for a cylindrical capacitor the electric field between the electrodes varies radially as the inverse of the radial coordinate.

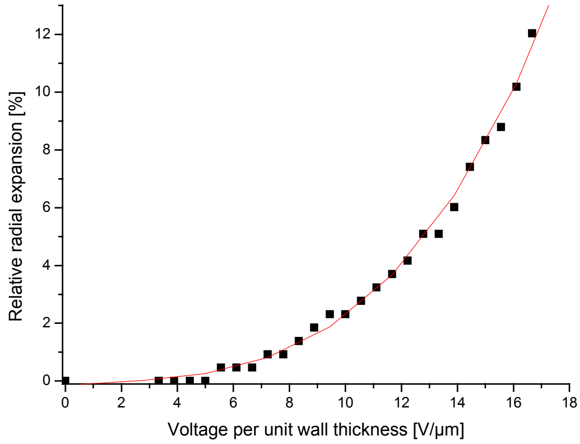

Fig. 25: Electrically-induced relative radial expansions of a prototype cylindrical actuator.

8 Future developments

The concept described above is currently under deeper investigation. FEM simulations are being performed in order to study the effect of different parameters of the system, such as sample dimensions, material elastic modulus, material dielectric strength (in order to increase the applicable voltages per unit thickness), etc. In particular, estimations about actuation forces achievable from different types of silicone elastomer are being evaluated. Future short-term investigations will include, firstly, a thorough analysis of the proposed concept by using non-linear models, in order to achieve more precise estimates of the system performance. Secondly, a first prototyping phase, aimed at integrating a few actuation modules, which is of course needed as a validation of theoretical analyses.

9 Conclusions

This study report has presented results obtained in the assessment of novel bio-inspired concepts for the development of distributed actuation systems potentially suitable for space applications. Specific simple solutions have been conceived by considering the use of dielectric elastomer actuators, which currently represent one of the most performing categories of EAP-based devices for electromechanical transduction.

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APPENDIX. Materials and technologies for distributed actuation: a concise survey of the state of the art

This Appendix reports a concise review of the most diffused actuation technologies that have already been used or have the potential to be used for distributed actuation systems. For the considered techniques, the different working principles, implementations and typical properties are briefly reported.

A1. Electrorheological fluids

Electrorheological (ER) fluids basically consist of particles that are held in suspension by a non-conducting liquid. The suspending liquid, which should have a high electrical resistivity, is typically a low-viscosity hydrocarbon or silicone oil. The particles dispersed in this liquid are commonly metal oxides, aluminosilicates, silica, organics, or polymers. In particular, the particles are very small (order of 1 μm) and have a sufficiently low concentration to allow the fluid to maintain a relatively low viscosity in the absence of an applied electric field [1].

A1.1 Actuation Principle

The electrorheological effect occurs in an ER fluid when an electric field is applied causing the uniformly dispersed solid particles to become polarized. Once polarized, they begin to interact with each other, and form chain-like structures, parallel to the electric field direction, connecting the two electrodes (Figure 1.1). Upon further intensification of the electric field, the chains begin to form thicker columns.

A change in the suspension's rheological properties is associated with this change in its structure. The columnar particle structures give the fluid a greater yield stress. Upon removing the electric field, the particles lose their polarization and return to their freely roaming state. The period of time over which these events occur is on the order of milliseconds [2].

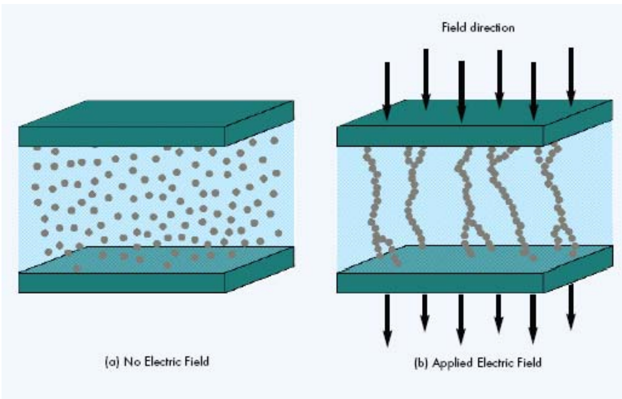


Figure 1.1:Actuation principle of ER fluids (from [2]).

The electric field required to induce rheological changes of ER fluid can be of the order of 1-10 kV/mm [1]. Typically, the current densities of ER fluids are between 10^{-6} and 10^{-3} A/cm^2 [3]. Current density measurements are used to predict the power consumption of a particular ERF. Yield stresses in conventioanl ER fluids range from approximately 100 Pa to over 3 kPa [3].

The properties of ER fluids can be modified by varying the components and compositions of the particles and liquid. In general, by increasing the concentration of particles in the fluid or by increasing the intensity of the applied field an increase the magnitude of the ER effect is achieved.

The properties of these fluids also depend on particle size and density, carrier fluid properties, additives, and temperature.

A higher concentration of the volume fraction of the dispersed particulate phase can give the fluid a much higher ER effect, but at the same time can cause problems. Sedimentation is a major factor, since higher concentrations of solid particles increases the amount of settling that will occur. The other potential problem is an increase in the zero-field viscosity.

The most obvious property affected by temperature is viscosity, which decreases as temperature increases. The dynamic yield strength also decreases with an increase in temperature. The more extensive change in dynamic yield strength for ER fluids is due primarily to changes in conductivity and relative permittivity of the particle and oil components of the fluid over the temperature range.

A1.2 Applications

The electrically controlled rheological properties of ERFs can be beneficial to a wide range of technologies requiring damping or resistive force generation.

Examples of applications are active vibration suppression and motion control. Several commercial applications have been explored, mostly in the automotive industry for ERF-based engine mounts, shock absorbers, clutches and seat dampers.

Other applications include haptic devices [4]. For instance, high yield stresses, combined with their small sizes can result in miniature haptic devices that can easily fit inside the human palm without creating any obstructions to human motion.

ERFs do not require any transmission elements to produce high forces, so direct drive systems can be produced with less weight and inertia.

The possibility of controlling the fluids' rheological properties gives designers of ERF-based haptic systems the possibility of controlling the system compliance.

ERFs respond almost instantly (milliseconds). This can allow high bandwidth controls. One of the main concerns that a designer of ERF-based haptic interfaces may have is the need for high voltages to develop the forces and compliance required. This has two consequences: a) an increases of the complexity of the driving electronic system; b) the occurrence of safety issues related to human operators. However, nowadays low power, small size circuits can be used to generate the required high voltage using very low currents (of the order of 1 μA). Consequently, the required power can become low (of the order of 1 mW), with no hazard for human operators.

A1.3 Examples of ER system and application

Virtual reality and telepresence, enhanced with haptic (i.e. tactile and force) feedback systems, represent new technical areas for applications of ER systems.

A novel ERF-based haptic system is called MEMICA (remote MEchanical MIrroring using Cotrolled stiffness and Actuators) [5]. MEMICA is intended to provide human operators an intuitive and interactive feeling of the stiffness and forces in remote or virtual sites in support of space, medical, underwater, virtual reality, military and field robots, performing dexterous manipulation operations.

MEMICA is currently being sought for use to perform virtual telesurgeries as shown in Figure 1.2 [5,6]. It consists of miniature Electrically Controlled Stiffness (ECS) elements and Electrically Controlled Force and Stiffness (ECFS) actuators that mirror the stiffness and forces at remote/virtual sites.

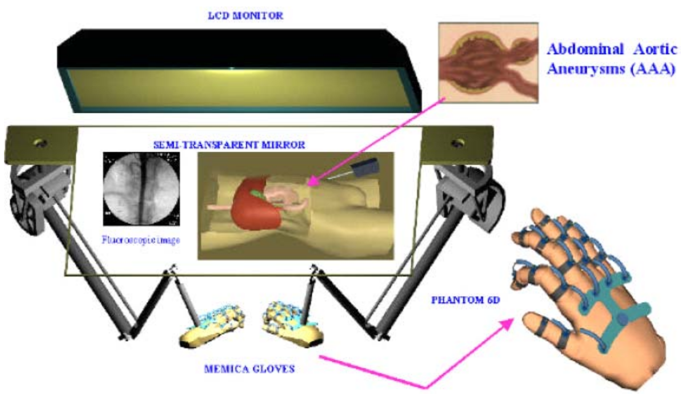


Figure1.2: Virtual reality robotic telesurgery simulations using MEMICA haptic system (from [7]).

The ECS elements and ECFS actuators which make use of ERFs to achieve this feeling of remote, virtual forces are placed at selected locations on an instrumented glove to mirror the forces of resistance at the corresponding locations in the robot hand.

The ECS element consists of a piston that is designed to move inside a sealed cylinder filled with ER fluid. The stiffness that is felt via the ECS element is electrically modified by controlling the flow of ER fluid through slots on the side of the piston (Figure 1.3) [8].

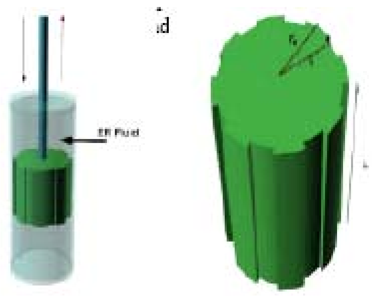


Figure 1.3: MEMICA: ECS element and its piston (from [7]).

To control the stiffness of the ECS element, a voltage is applied between electrodes facing the slot, affecting the ability of the liquid to flow. Thus, the slot serves as a liquid valve, since the increased viscosity decreases the flow rate of the ER fluid and varies the stiffness felt.

To increase the stiffness bandwidth from free flow to maximum viscosity, multiple slots are made along the piston surface. To wire such a piston to a power source, the piston and its shaft are made hollow and electric wires are connected to electrode plates mounted on the side of the slots. The inside surface of the ECS cylinder surrounding the piston is made of a metallic surface and serves as the ground and opposite polarity. When a voltage is applied, an electric field is developed through the ER fluid along the piston channels, altering its viscosity. As a result of the increase of the ER fluid viscosity, the flow is slowed and resistance to external axial forces increases.

To produce complete emulation of a mechanical "tele-feeling" system, it is essential to use actuators in addition to the ECS elements in order to simulate remote reaction forces. Such a haptic mechanism needs to provide both active and resistive actuation. The active actuator can mirror the forces at the virtual/remote site by pulling the finger or other limbs backward.

A schematic description of the ECFS actuator is shown in Figure 1.4. The actuator consists of two pistons (brake elements) and two electromagnetic cylinders (pusher element).

Similar to ECS, each piston has several small channels with a fixed electrode plate. When an electric field is induced between the piston anode and cylinder cathode, the viscosity of the ER fluid increases and the flow rate of the fluid though the piston channel decreases securing the piston to the cylinder wall. Each of the electromagnetic cylinders consists of a coil and a ferromagnetic core integrated within the piston. When a current impulse is passed through the winding, an electromagnetic field is induced and depending on the current direction, the cylinder moves forward or backward.

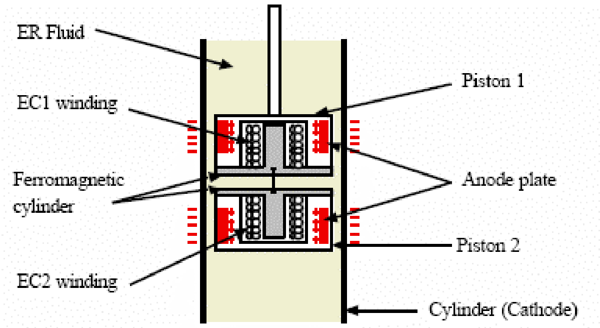


Figure1.4: MEMICA: ECFS actuator configuration (from[7]).

At each cycle, the pistons move forward or backward with very small displacement (<1.5 mm). The duration of each cycle is close to a millisecond, corresponding to the response time of the ERF. The ECFS actuator can then reach a speed higher than 15 cm/s with a piston displacement equal to 0.5 mm at 3 ms cycle duration. The electromagnetic cylinder is designed to produce the same force as the resistive force of the piston inside the ER fluid, which is about 15 N.

A2. Magnetorheological fluids

Magnetorheological (MR) fluids have a similar composition to ER fluids in that they typically contain a dispersed, polarizable, particulate phase suspended in a carrier fluid. However, unlike the ER fluids, MR fluids use ferromagnetic or paramagnetic solid particles. These particles are usually within an order of magnitude of a micrometer in diameter. It is common for them also to contain surfactants and other additives.

A typical MR fluid consists of 20-40 vol % of relatively pure, 3-10 μm-diameter iron particles, suspended in a carrier liquid such as mineral oil, synthetic oil, water or glycol.

Table 2.1: Basic composition and density of four commercial MR fluids (from[9]).

Commercial MR fluid	Percent iron by volume	Carrier fluid	Density(g/ml)
MRX-126PD	26	Hydrocarbon oil	2.66
MRX-140ND	40	Hydrocarbon oil	3.64
MRX-242AS	42	Water	3.88
MRX-336AG	36	Silicone oil	3.47

A2.1 Actuation Principle

The magnetorheological effect is similar to the ER effect, but obviously, instead of an electric field, a magnetic field is applied to polarize the particles [11].

Magneto-rheological (MR) fluids respond to a magnetic field with a dramatic change in rheological behaviour (Figure 2.1). These fluids can reversibly and instantaneously change from a free-flowing liquid to a semi-solid with controllable yield strength when exposed to a magnetic field. In the absence of an applied field, MR fluids are reasonably well approximated as Newtonian liquids.

Figure 2.1: Rheological behaviour of a MR fluid (from[9]).

MR fluids made from iron particles exhibit maximum yield strengths of 50-100 kPa for applied magnetic fields of 150-250 kA/m. MR fluids are not highly sensitive to moisture or other contaminants that might be encountered during manufacture and usage. Further, because the magnetic polarization mechanism is unaffected by temperature, the performance of MR-based devices is relatively insensitive to temperature over a broad temperature range (including the range for automotive use).

A2.2 MR vs ER Fluids

A comparison of the typical properties of ER and MR fluids is given in Table 2.2.

Table 2.2: Typical MR e ER fluid properties (from[10])

	MR	ER
Max Yeld Stress	50-100kPa	2-5kPa
Max Field	~250kA/m (limited by saturation)	~4kV/mm (limited by breakdown)
Viscosity	0.1-1.0 Pa·s	0.1-1.0 Pa·s
Operable Temp. Range	-40 to +150 °C (limited by carrier fluid)	+10 to +90 °C(ionic,DC) -25 to +125 °C(non-ionic,AC)
Stability	Unaffected by most impurities	Cannot tolerate impurities
Response Time	<milliseconds	<milliseconds
Density	3-4 g/cm^3	1-2 g/cm^3
Max Energy Density	0.1 Joule/cm^3	0.001 Joule/cm^3
Power Supply (typical)	2-25V@1-2A (2-50 watts)	2-5kV@1-10mA (2-50watts)

Advantages of MR fluid technology:

- Yield Stress: MR fluids have a yield stress an order of magnitude greater than their ER counterpart [11].
- Power: ER and MR fluid devices have similar power requirements. MR devices can be run directly on common low-voltage power sources. This power consumption aspect translates into a lower cost for MR fluids as well as a safer system.
- Stability: ER fluids are highly sensitive to contaminants or impurities. Contaminants have little effect on the MR fluids and can effectively operate over a broad temperature range [11].

Disadvantages of MR fluid technology:

- Sedimentation: MR fluids present a strong tendency to sedimentation, in that once a significant amount of the particles coagulate, being difficult to redisperse them.

- Organic fluids: for both ER and MR fluids the carrier fluid is usually organic. Organic fluids have problems with degradation, polymerization, flammability, bacterial growth, and can also be incompatible with other components in systems where they are used [12].

A2.3 Example of MR system and application

Haptic interfaces based on magnetorheological fluids have been described [13]. Such systems use MR fluids as means with controllable compliance, damping, and creep. Possible fields of application could be the surgical training in minimally invasive surgery and open surgery. This approach of using an MR fluid is justified by the observation that viscoelastic properties of the biological tissues could be mimicked by magnetically tuning the rhelogical properties of the fluid.

In the case of minimally invasive surgery, the fluid could be incorporated in the handle of a surgical end-effector, whereas in the open surgery the operator would interact with a haptic box containing the fluid. Examples of devices include pinch grasp and immersive configurations [13].

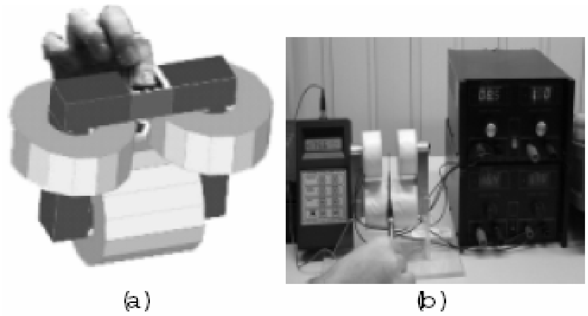


Figure 2.2: Examples of MR fluid-based pinch grasp devices (from [13]).

Examples of pinch grasp devices consist of a MR fluid that is positioned in the air-gap of an electromagnet within a latex sleeve allowing the pinch grasp manipulation (Fig. 2.2) [13].

Example of immersive devices consist of a given volume of MR fluid placed within a box surrounded by solenoids so that a hand can be introduced and interact with the fluid (Fig. 2.3) [13].

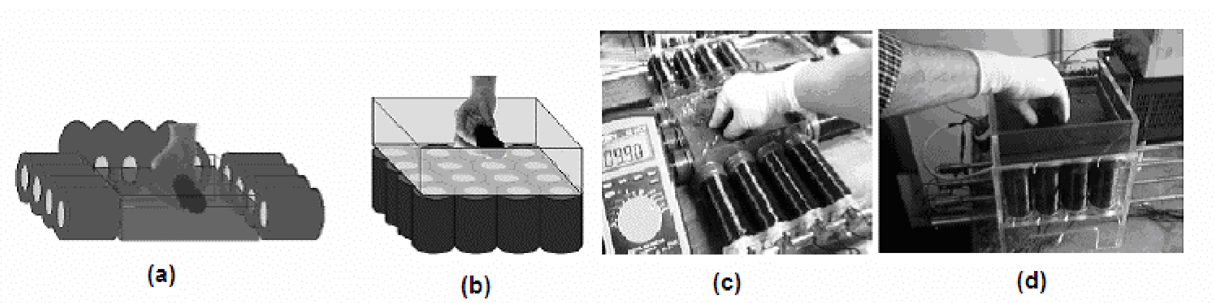


Figure 2.3: Examples of MR fluid based immersive devices (adapted from [13]).

Experimental psychophysical tests were performed in order to qualitatively assess performances of such systems [13].

A3. Piezoelectric materials

Piezoelectrics are materials that exhibit an electrical polarization with an applied mechanical stress (direct effect), or a dimensional change with an applied electric field (converse effect). They are used for both sensing and actuating devices.

A3.1 Actuation principle

A piezoelectric material produces an electric charge when a mechanical stress is applied (the material is squeezed or stretched). Conversely, a mechanical deformation (the material shrinks or expands) is produced when an electric field is applied. This effect is formed in crystals that have no center of symmetry. Each molecule that make up the crystal has a polarization : one end is more negatively charged and the other end is positively charged, forming a so-called dipole. This is a result of the atoms that make up the molecule and the way the molecules are shaped. The polar axis is an imaginary line that runs through the center of both charges on the molecule. In a monocrystal the polar axes of all of the dipoles lie in one direction. A monocristal is symmetrical.. In a polycrystal, there are different regions within the material that have a different polar axis. It is asymmetrical because there is no point at which the crystal could be cut that would leave the two remaining pieces with the same resultant polar axis.

In order to produce the piezoelectric effect, the polycrystal is heated under the application of a strong electric field. The heat allows the molecules to move more freely and the electric field forces all of the dipoles in the crystal to line up and face in nearly the same direction Figure 3.1.

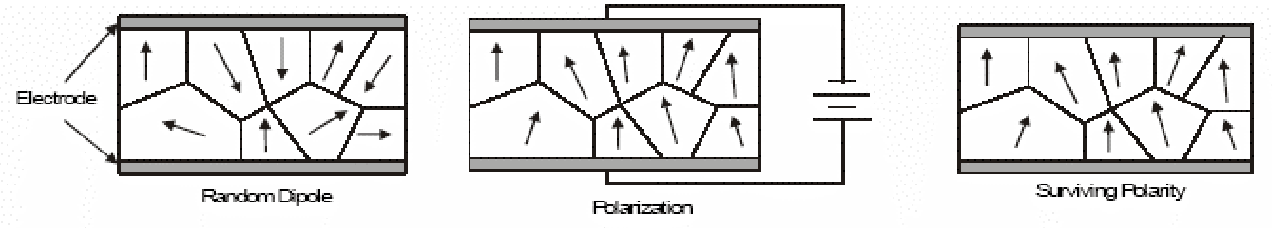


Figure 3.1: Polarization of a piezoelectric material (from [14]).

Figure 3.2 illustrates the piezoelectric effect. In particular, Figure 3.2a shows the piezoelectric material without a stress or charge. If the material is compressed, then a voltage of the same polarity as the poling voltage will appear between the electrodes (Figure 3.2b) If stretched, a voltage of opposite polarity will appear (Figure 3.2c). Conversely, if a voltage is applied the material will deform. A voltage with the opposite polarity as the poling voltage will cause the material to expand (Figure 3.2d) and a voltage with the same polarity will cause the material to compress (Figure 3.2e). If an AC signal is applied then the material will vibrate at the same frequency as the signal (Figure 3.2f).

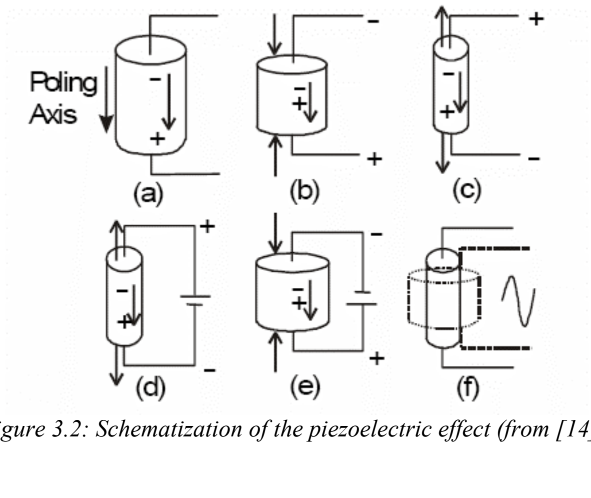


Figure 3.2: Schematization of the piezoelectric effect (from [14]).

Piezoceramics (such as PZT) and piezopolymers (such as PVDF) are usually produced in thin sheets with films of metal deposited on the opposite surfaces to form electrodes. Piezoceramics are brittle and stiff, while piezopolymers are tough and flexible. In particular, piezopolymers are good candidates for sensing because of their small stiffness, which adds minimum local stiffening to the host structure, while piezoceramics are better suited for actuation, due to their greater elastic modulus for effective mechanical coupling to the structure.

Piezoelectric materials have been found to be very attractive for smart structure applications. They are light and can be readily attached or embedded into structures. They are suitable to develop distributed sensors and actuators.

Devices using piezoelectrics include: adaptive optics, hydrophones and sonobuoys, fuse devices, depth sounders, thickness gauging, flaw detection, level indicators,alarm systems, strain gauges, airplane beacon locators, fetal heart detectors and tire pressure indicators, among many others [2].

A3.2 Examples of distributed actuators based on piezoelectric devices

A3.2.1 Braille displays

Braille interfaces generate Braille characters for blind people. Such systems work by raising and lowering pins, in response to an electronic signal. Many Braille displays made of actuators containing piezoelectric crystals have been proposed [15]. Figure 3.3 shows one example.

Figure 3.3: Examples of refreshable Braille display based on piezoelectric actuators (from [15]).

A3.2.2 Tactile displays

Several tactile displays based on piezoelectric actuators are today available. As an example, Fig. 3.4 shows a surface acoustic wave (SAW) tactile display consisting of a piezoelectric substrate and a slider [16,17]. By rubbing the substrate through the slider, tactile sensations can be felt under a control depending on the rubbing motion.

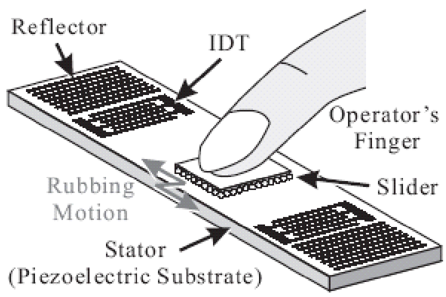


Figure 3.4: Basic structure of a SAW tactile display (from [16])

In order to excite standing waves in this tactile display, two interdigital trasducers (IDT) are formed on the piezoelectric substrate. The standing wave is generated in the center of the substrate. The operator then rubs on the substrate surface through a slider [16].

A4. Microelectromechanical systems

Microelectromechanical systems (MEMS) reepresent the technology of the very small. They merge at the nanoscale into Nanoelectromechanical Systems (NEMS) [18].

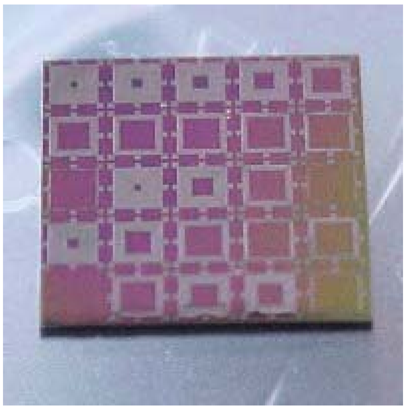


Fig. 4.1: Example of MEMS device (from [18]).

MEMS devices refer to mechanical components on the micrometre size and include 3D lithographic features of various geometries. Figure 4.1 shows an example. They are typically manufactured using planar processing similar to semiconductor processes, such as surface micromachining and/or bulk micromachining. These devices generally range in size from a micrometre to a millimetre. Due to MEMS' large surface area to volume ratio, surface effects such as electrostatics and wetting dominate volume effects such as inertia or thermal mass. They are fabricated by using modified silicon fabrication technology (used to make electronics), molding and plating, wet etching and dry etching , electro discharge machining, and other technologies capable of manufacturing very small devices.

A4.1 MEMS applications

Common applications of MEMS include:

- inkjet printers, which use piezoelectrics or bubble ejection to deposit ink on paper.
- accelerometers in modern cars for airbag deployment in collisions.
- MEMS gyroscopes used in modern cars and other applications to detect yaw; e.g. to deploy a roll over bar or trigger dynamic stability control.
- pressure sensors e.g. car tire pressure sensors, and disposable blood pressure sensors.
- Displays: for example, microdevices having on their surface several hundred thousand micromirrors.
- Optical switching technology used for data communications.

A4.2 MEMS materials

MEMS technology can be implemented using a number of different materials and manufacturing techniques. The choice will depend on the device being created and the market sector in which it has to operate.

Silicon is the material used to create almost all integrated circuits used in consumer electronics in the modern world. The economies of scale, ready availability of highly accurate processing and ability to incorporate electronic functionality make silicon attractive for a wide variety of MEMS applications. Silicon also has significant advantages engendered through its material properties. In single crystal form, silicon is an almost perfect Hookean material, meaning that when it is flexed there is virtually no hysteresis and hence almost no energy dissipation. As well as making for highly repeatable motion, this also makes silicon very reliable as it suffers very little fatigue and can have service lifetimes in the range of billions to trillions of cycles without breaking. The basic techniques for producing all silicon based MEMS devices are deposition of material layers, patterning of these layers by lithography and then etching to produce the required shapes.

Even though the electronics industry provides an economy of scale for the silicon industry, crystaline silicon is still a complex and relatively expensive material to produce. Polymers on the other hand can be produced in huge volumes, with a great variety of material characteristics. MEMS devices can be made from polymers by processes such as injection moulding, embossing or stereolithography and are especially well suited to microfluidic applications such as disposable blood testing cartridges.

Metals can also be used to create MEMS elements. While metals do not have some of the advantages displayed by silicon in terms of mechanical properties, when used within their limitations, metals can exhibit very high degrees of reliability.

Metals can be deposited by electroplating, evaporation, and sputtering processes.

Commonly used metals include Gold, Nickel, Aluminum, Chromium, Titanium, Tungsten, platinum, and silver.

A4.3 MEMS Processes

Deposition Processes

One of the basic building blocks in MEMS processing is the ability to deposit thin films of material. In this text we assume a thin film to have a thickness anywhere between a few nanometer to about 100 micrometer. Commonly used deposition processes are: Electroplating, Sputtering, Physical Vapour Deposition (PVD) and Chemical Vapour Deposition (CVD).

Photolithography

Lithography in the MEMS context typically consist of a transfer of a pattern to a photosensitive material by selective exposure to a radiation source, such as light. A photosensitive material is a material that experiences a change in its physical properties when exposed to a radiation source. If we selectively expose a photosensitive material to radiation (e.g. by masking some of the radiation) the pattern of the radiation on the material is transferred to the exposed material, as the properties of the exposed and unexposed regions are different. The exposed region can then be removed or treated providing a mask for the underlying substrate. Photolithography is typically used with metal deposition, wet and dry etching.

Etching Processes

There are two basic categories of etching processes: wet and dry etching. In the former, the material is dissolved when immersed in a chemical solution. In the latter, the material is sputtered or dissolved using reactive ions or a vapor phase etchant.

Wet Etching

This is the simplest etching technology. All it requires is a container with a liquid solution that will dissolve the considered material. Unfortunately, there are complications since usually a mask is desired to selectively etch the material. One must find a mask that will not dissolve or at least etches much slower than the material to be patterned. Secondly, some single crystal materials, such as silicon, exhibit anisotropic etching in certain chemicals. Anisotropic etching in contrast to isotropic etching means different etch rates in different directions in the material.

RIE etching

In reactive ion etching (RIE), the substrate is placed inside a reactor in which several gases are introduced. A plasma is struck in the gas mixture using an RF power source, breaking the gas molecules into ions. The ions are accelerated towards, and reacts at, the surface of the material being etched, forming another gaseous material. This is known as the chemical part of reactive ion etching. There is also a physical part which is similar in nature to the sputtering deposition process. If the ions have high enough energy, they can knock atoms out of the material to be etched without a chemical reaction. It is a very complex task to develop dry etch processes that balance chemical and physical etching, since there are many parameters to adjust. By changing the balance it is possible to influence the anisotropy of the etching, since the chemical part is isotropic and the physical part highly anisotropic the combination can form sidewalls that have shapes from rounded to vertical.

DRIE etching

A special subclass of RIE which continues to grow rapidly in popularity is deep RIE (DRIE). In this process, etch depths of hundreds of micrometres can be achieved with almost vertical sidewalls. The primary technology is based on the so-called "Bosch process", named after the German company Robert Bosch which filed the original patent, where two different gas compositions are alternated in the reactor. The first gas composition creates a polymer on the surface of the substrate, and the second gas composition etches the substrate. The polymer is immediately sputtered away by the physical part of the etching, but only on the horizontal surfaces and not the sidewalls. Since the polymer only dissolves very slowly in the chemical part of the etching, it builds up on the sidewalls and protects them from etching. As a result, etching aspect ratios of 50 to 1 can be achieved. The process can easily be used to etch completely through a silicon substrate, and etch rates are 3-4 times higher than wet etching.

Bulk micromachining

Bulk micromachining is similar to deep etching but uses a different process to remove silicon. Bulk micromachining typically uses alkaline liquid solvents, such as potassium hydroxide, to dissolve silicon which has been left exposed by the photolithography masking step. These alkali solvents dissolve the silicon in a highly anisotropic way, with some crystallograpic orientations dissolving up to 1000 times faster than others. Such an approach is often used with very specific crystallographic orientations in the raw silicon to produce v-shaped grooves. The surface of these grooves can be atomically smooth if the etch is carried out correctly with dimensions and angles being extremely accurate. Metals are also often used as masks for dry and wet etching other materials, depending on the selectivity of the metal to the etchant.

A4.4 Example of MEMS based distributed actuators

Tactile displays made of arrays of MEMS actuators have been proposed [19]. The purpose is to develop high-bandwidth tactile interfaces for stimulating the user’s tactile sense. They find two major classes of applications: (1) Tactile interfaces mounted on machines could indicate the state of the machine--such as the remaining charge in a battery--or it might respond to the operator's touch in subtle ways not possible with conventional controls; (2) Tactile interfaces attached to the human body--for example, through a glove or wrist band--could be used with wearable computers or communication devices for both input and output.

MEMS stimulators consisting of two gas- or fluid-filled chambers as shown in Figure 4.2 have been proposed [19].

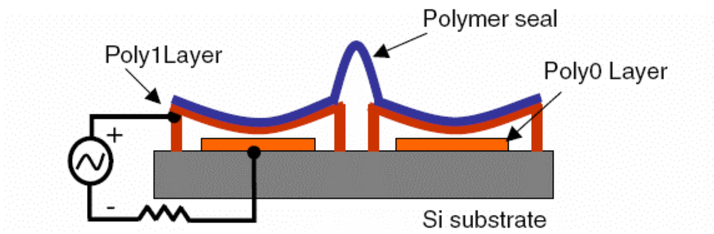


Figure 4.2: Surface micro-machined actuator with polysilicon membrane (from [19]).

The chambers are covered and sealed by a common membrane such that when the membrane covering the outer chamber is displaced by electrostatic force, the membrane covering the inner chamber is also displaced by the movement of the fluid. A mesh based aluminum membrane (Figure 4.3) has been proposed to produce a variable deflection surface for acoustic MEMS [19].

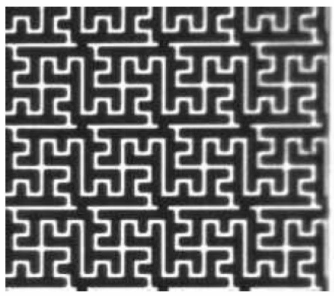


Figure 4.3: Mesh based aluminum membrane (from [19]).

This concept was adopted for the design of CMOS fabricated tactile actuators (Figure 4.4) [19].

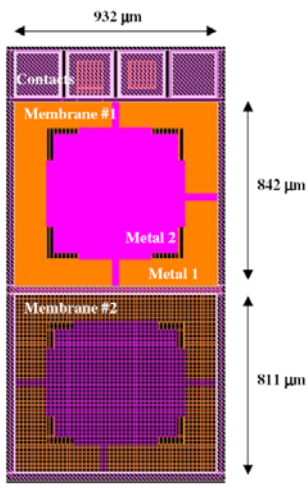


Figure4.4: CMOS tactile actuator layout (from [19]).

Each actuator was designed with two aluminum layers for the inner and outer chambers of the mesh-patterned membrane. The two regions are electrically isolated by an oxide layer, which raises the inner chamber metal layer above the outer region. This provides the ability to actuate the pneumatic compression with the outer chamber while measuring the change in capacitance with the inner Metal 2 layer.

A5. Electroactive Polymers

Electroactive polymers (EAPs) consist of materials capable of changing dimensions and/or shape in response to an electrical stimulus. The EAP materials are classified in two major categories: ionic EAPs, activated by an electrically-induced transport of ions or molecules, and electronic EAP, activated by an external electric field and by Coulombian forces. Table 5.1 summarizes this classification, listing for both types of EAPs the most representative materials.

Table 5.1. Classification of electroactive polymers

Mechanism of activation	Materials
Mass/ion transport (ionic EAPs)	Conducting polymers Polyelectrolyte gels Ionipolymer-metal composites Carbon nanotubes
Electric field (electronic EAPs)	Dielectric elastomers Piezoelectric polymers Electrostrictive polymers Liquid crystal elastomers

Materials belonging to the two EAP classes present very different properties and actuating performances, leading to the realization of devices showing unlike values of typical figures of merit, such as generable active strains and stresses, required driving voltages, efficiency, lifetime, chemical stability and reliability.

Despite the very low voltages (order of 1 V) required by ionic EAPs for their electromechanical activation, they typically present higher response times and lower stability, reliability and durability with respect to those of the electronic type polymers. Nevertheless, the second ones have to be operated with considerably higher voltages (electric fields of the order of 10-100 V/µm are typically necessary), even though progresses towards the reduction of driving fields are in course, as it will be described in the next sub-Sections.

So far, not all the listed materials have reached a sufficient technological development for actuation-oriented applications. For instance, liquid crystal elastomers do not currently have any practical utility for macroscopic actuation, although interesting electromechanical performances have been recently reported [20]. Similarly, carbon nanotube actuators [21] do not show at present any significant macroscopic potentiality. Therefore, both these kinds of materials will not be taken in consideration here, while electroactive polymers with most relevant actuation performances will be briefly described below.

A5.1 Polyelectrolyte Gels

A polymer gel consists of an elastic cross-linked polymer network and a fluid filling its interstitial space. The network holds the liquid and gives the gel its typical compactness. Gels are wet and soft and look like a solid polymer material, capable of undergoing large deformations (higher than 40%).

Polymer gels can be easily deformed by external stimuli, in order to generate force and execute work. If such responses can be translated from the microscopic level to a macroscopic scale, a conversion of chemical free energy into mechanical work is realized [22]. In particular, polyelectrolyte gels undergo reversible order-disorder transitions following changes in temperature, pH and solvents. For instance, they swell in organic solvents and undergo spontaneous motion when placed in water.

Moreover, if a water-swollen cross-linked polyelectrolyte gel is inserted between a pair of planar electrodes and a dc voltage is applied, it shows anisotropic contraction and concomitant fluid exudation. Such an electrically induced contraction of gels can be used for electromechanical actuation.

A5.2 Ionic Polymer-Metal Composites

Ionic polymer metal composites (IPMCs) are actuation materials capable of showing large deformations in presence of low applied voltages. These materials have in their molecular chain many ionizable groups, which can be dissociated in various solvents, showing a resulting net charge, which is compensated by the presence of counterions [23]. They operate best in a humid environment and can be made as encapsulated actuators to operate in dry conditions.

The essence of the electromechanochemical deformations shown by IPMCs is represented by their susceptibility to interact with externally applied fields. If the interstitial space of the network is filled with a liquid containing ions, electrophoretic migration (due to an imposed electric field) of these ions inside the structure can cause the macromolecular network to be deformed accordingly [23,24]. For a solvent such as water, the local swelling and de-swelling of the membrane can be controlled, depending on polarity of the nearby electrode. Most studied IPMC actuators use a film of Nafion-117 (Du Pont) as a perfluorinated ion exchange membrane (IEM), on both sides of which platinum electrodes are deposited. Typical thickness values of such devices are of the order of 0.20 mm.

A space application of this kind of EAP actuators has been proposed by JPL (Jet Propulsion Laboratory, U.S.A.). It relates to the use of an IPMC bender device as a dust wiper for camera lenses of a space rover [25,26]. A prototype of the device, conceived for the MUSES-CN’s Nanorover, 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 [27].

A5.3 Conducting Polymers

Electron conducting polymer (CP) actuators can generate large active stresses (tens of MPa and more) with low electrical potential differences (few Volts). CP based devices consist of at least three elements: a conducting polymer (in film or fiber form), an electrolyte (possibly in solid state) and a counter electrode (eventually another CP).

In conducting polymers energy transduction originates from the doping process in the polymeric chain. Indeed, oxidation of the polymer chain changes its bound charge and intercalation (or de-intercalation) of doping ions occurs, causing structural and dimensional changes of the material to restore electroneutrality [28,29]. Active strains of the order of 1-10% and active stresses of several tens of MPa are possible.

Two functional configurations are typically used: electrolyte storage and electrode storage. In the electrolyte storage configuration two different conducting polymers are employed: a p-doped polymer (with an anion as dopant) and a n-doped polymer (with a cation as dopant). The electrolyte contains the same ions acting as polymer electrode dopants and it acts as dopant storage. By imposing a periodic electrochemical stimulation, two processes can be distinguished: during a semicycle, both polymers are doped with ions from the electrolyte and they expand their volume; in the following semicycle, both electrodes are de-doped and ions come back to the electrolyte, causing a reduction of electrode volume.

In the electrode storage configuration two polymer electrodes doped with the same ion are used (cationic or anionic) and the electrolyte has just to provide a ionic conductivity between them. The two polymers work alternatively as dopant storage electrodes. This implies that during one semicycle of a periodic stimulation a polymer is doped, while the other one is de-doped; so one electrode shrinks and the other elongates. The roles of the electrodes are exchanged in the second part of the cycle.

The electrolyte storage configuration can be used to implement linear actuators [30], while the second one is advantageous for bending devices [31].

Conducting polymer unimorph bending actuators are typically made of a polymer film sputtered on one side with an electrode and immersed in an electrolyte, along with a spatially separated counter electrode. Electrochemical reversible doping of the polymer produces an expansion of the electrode and a bending of the actuator. Bending bimorphs have anode and cathode films of conducting polymer deposited on the opposite sides of a support, used as a bidirectional bending element.

Fiber-shaped linear actuators consist of a fiber of conducting polymer covered by a solid polymer electrolyte and a counter electrode made of either conducting polymer or copper wire. Such a device consents the generation of linear motion.

Regardless the particular actuating configuration, it is relevant to underline that the diffusion-driven energy transduction mechanism in conducting polymer actuators limits their response speed, while the incomplete reversibility of the electrochemical doping and dedoping affects their cycle life time. Despite recent improvements obtained with ionic liquid electrolytes [32], both these factors still negatively influence the applicability of currently available conducting polymer actuators.

A5.4 Electrostrictive Polymers

Electrostriction is one of the main electro-mechanical coupling phenomena shown by dielectric materials. It is responsible of a quadratic dependence of the material active strain on the polarization due to an applied electric field. Therefore, for materials showing a linear relation between polarization and applied field, the electrostrictive strain depends on the square of the field.

Most notable examples of electroactive polymers manifesting a relevant electrostrictive effect are represented by some copolymers of poly(vinylidene fluoride) (P(VDF)) with trifluoroethylene (P(VDF-TrFE)), with tetrafluoroethylene (P(VDF-TFE)) and with esafluoropropylene (P(VDF-HFP)). These materials are ferroelectric (and therefore piezoelectric and pyroelectric too) and present typically a semi-crystalline molecular structure (crystals immersed in an amorphous matrix).

Such polymers have typical elastic moduli of the order of 1-10 GPa. By applying a high electric field (order of 100 V/µm) to an electron-irradiated P(VDF-TrFE), strains up to 4% have been reported [33]. Recent investigations showed that a drastic reduction of the driving electric fields of electrostrictive polymers can be obtained by mixing with the polymer matrix a highly dielectric component. In particular, composite materials realized by dispersing a copper-phthalocyanine (CuPc) in a matrix of P(VDF-TrFE) have shown a 2% strain with an applied electric field of 13 V/µm, less than one sixth of the usual value necessary for the pure polymer matrix [34].

Actuators realized with electrostrictive ferroelectric EAP can be operated in air, water or vacuum and in a wide range of temperature. However, the law values of currently achievable strains prevent their use for macro-scale applications.

A5.5 Dielectric Elastomers

Insulating rubbery polymers having a low elastic modulus can exhibit large deformations if subject to a high electric field. In fact, when a thin film of dielectric elastomer is sandwiched between two compliant electrodes (e.g. made of carbon conductive grease) and a 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 (Figure 3) [35,36].

By assuming a dielectric elastomer as a linearly elastic and dielectric body, having a Young's modulus Y and a relative dielectric constant ε_r, subject to an electric field E, linear strains S along the electric field direction can be described by the following equation [35,36]:

$$S = -\frac{1}{Y}\varepsilon_0 \varepsilon_r E^2 \qquad (5.1)$$

where ε_0 is the free-space dielectric permittivity (ε_0 =8.85x10^{-12} F/m).

Acrylic elastomers 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 [36]. In particular, some acrylic polymers have exhibited 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 [36]. The excellent figures of merit possessed by dielectric elastomers in several respects (high actuation strains and stresses, low response times, high efficiency, stability, reliability and durability) make them the most performing materials currently available for polymer actuation.

The price for achieving such high-level capabilities is represented by the necessary high driving electric fields. For a definite polymer thickness, such field levels can be reached by using high voltages (even though accompanied by low currents, owing to the capacitive nature of these devices), which may be disadvantageous in many applications. For this reason, in order to reduce the driving electric fields, polymers with a high dielectric constant are sought (Eq.5.1).

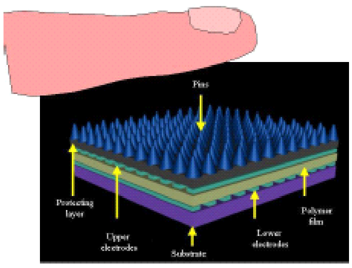
With respect to this, new highly dielectric elastomers can be realized by means of a composite approach. By filling an ordinary elastomer with a component showing a greater dielectric permittivity, it is possible to obtain a resulting material showing the fruitful combination of the advantageous matrix elasticity and filler permittivity. Such materials consent a reduction of the driving fields, as recently reported [37].

The first studies for space applications of dielectric elastomer actuators are rising 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 [38].

Typical device configurations used for dielectric elastomer actuation include planar devices, stacks, tubes, rolls, extenders, diaphragms, bimorph and unimorph benders, helical and folded structures, etc. [35,39-44].

A5.6 Examples of EAP-based distributed actuators

Several type of Braille-like tactile displays using electroactive polymers have been proposed. The aim of such interfaces s to reproduce textual and graphical information for blind persons. These tactile display typically consist of planar arrays of pins, actuated by electroactive polymers that create the tactile output by modulating the height of some pins (Fig. 5.1) [45].



(a)

Figure 5.1: Tactile interface to generate different textures on the finger tip (adapted from [46]).

As another example of use of EAP-based devices for distributed actuation, we mention here the case of systems developed with soft actuators, studied for instance for manipulations of soft and delicate objects. In particular, several systems of this type have been proposed by using IPMC actuators [47]. These actuators are fabricated by chemically plating platinum electrodes onto a perfluorosulfonic acid membrane. Applying a voltage to both platinum electrodes causes the element to bend, as shown in Fig. 5.2.

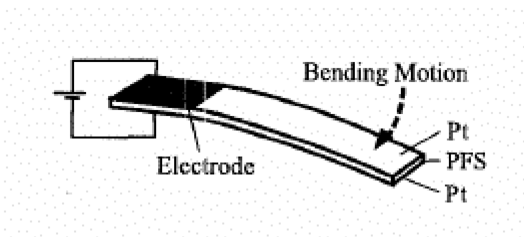


Fig. 5.2: IPMC bending actuator (from [47]).

Examples of studied applications of these actuator materials include active guide wires for micro catheters [48] and so-called elliptical friction drive (EFD) actuator elements [49]. The latter consist of actuators that generate driving forces by friction using IPMC elements. An example of a EFD element consists of two IPMC actuators, arranged as shown in Fig. 5.3. The whole structure is fixed so as to form the shape of an arch. When sinusoidal voltages with a phase difference are applied to the two IPMCs, the excited sinusoidal bending motions also have phase difference.

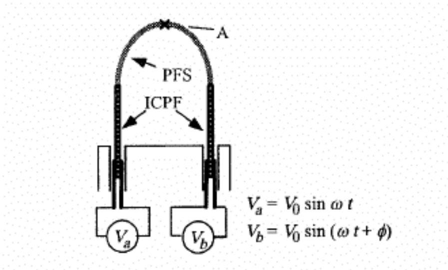


Fig. 5.3: Structure of an EFD actuator element (from [47]).

An array of such EFD devices can be used for distributed actuation, as shown in the example of Fig.5.4. In this case a number of EFD elements cooperatively apply a driving force to an object.

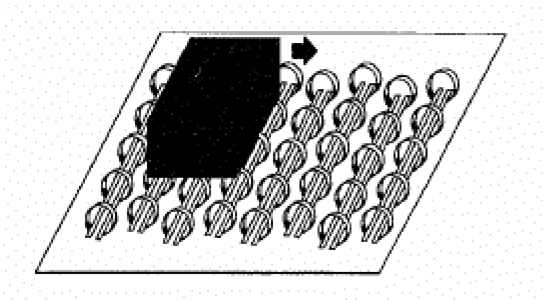


Fig. 5.4: Distributed actuation device consisting of multiple EFD elements (from [47]).

The driving principle is shown in Fig. 5.5. Adjacent elements make elliptical motions with a phase difference. On the planar contact face, a frictional force in the horizontal direction is generated alternately by adjacent elements, and the object is driven.

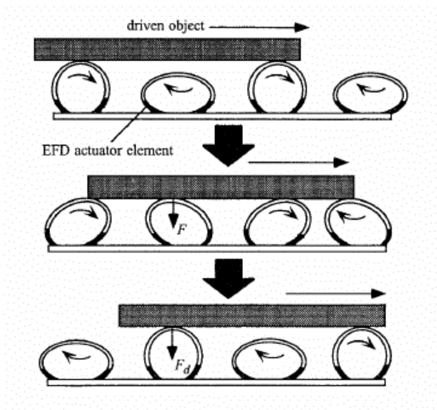


Fig. 5.5: Principle of distributed drive (from [47]).

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