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Abstract

This report deals with a preliminary feasibility study on the application of electroactive polymer (EAP) based devices for the actuation of a simplified model of a robotic locomotion system, intended by the European Space Agency to operate on the surface of Mars. The system, denominated "Mars jumping rover", has been conceived as an elastic sphere, with a radius of 1 m, capable to jump over obstacles, by using the actuation capabilities provided by an internal EAP-based linear electromechanical actuator. Following a review of the available EAP technologies, linearly contracting dielectric elastomer actuators have been identified as suitable devices and two possible solutions concerning their use have been proposed, modelled and evaluated via numerical simulations. By assuming for the actuator active contraction strains of -10% , achievable with the application of electric fields of about $25\text{-}30 \text{ V}/\mu\text{m}$, the best solution has revealed interesting simulated performances, enabling jumping of obstacle heights of the order of 10 cm, corresponding to the 5% of the diameter of the sphere.

Keywords: *electroactive polymers, EAP, artificial muscles, dielectric elastomers, dielectric elastomer actuator, polymer actuators, space systems, space rover, space exploration.*

1. Introduction: problem definition

In the frame of the ESTEC/Contract No. 18150/04/NL/MV this study team has performed for the European Space Agency (ESA) a preliminary feasibility study for a possible application of "EAP-based artificial muscles as an alternative to space mechanisms". In particular, according to the specifications provided by the Agency, it has been studied the use of EAP-based actuators for a simplified model of a robotic locomotion system. This system, denominated "Mars jumping rover", should operate on the surface of Mars with the capability to jump over obstacles, enabled by actuating functions offered by EAP-based actuators.

The study has been performed, according to the following ESA specifications:

SYSTEM: sphere

ACTUATION: a cylindrical bar placed inside the sphere and made of /or equipped with EAP-based artificial muscles, intended to provide the sphere the capability to jump over obstacles (e.g. rocks) under the effect of an adequate electric field.

DIMENSIONS:

- 1) diameter of the sphere: 1-10 m;
- 2) diameter of the bar: $\sim 10 \text{ cm}$;

MARS GRAVITY: 3.72 m/s^2 .

In order to propose solutions for this problem, this study team has performed a preliminary review of the available EAP technologies, in order to select EAP materials and configurations suitable for this application. Then, possible solutions using identified

materials and configurations have been proposed, modelled and evaluated via numerical simulations.

2. Review of EAP technologies

The great majority of traditional actuators (devices converting a definite form of energy into mechanical energy) developed by man are thermochemical, electromagnetic or pneumatic machines, which require to be coupled to specific mechanical accessories to transfer motion and forces to loads.

Despite the advanced state of such conventional motor technologies, there is a growing demand in fields such as mechatronics, robotics and bioengineering for polymer actuators with high power-to-weight and power-to-volume ratios, high efficiency and large degree of compliance, which would provide a major advance in several applications, involving critical and delicate tasks.

Actuation of space mechanisms represents certainly one of the most representative and challenging examples of such fields of application, since the high degree of performance and reliability required. Future space missions could benefit a lot from the use of polymer actuators, able to perform a functional mimicking of the superior actuating skills proper of human muscles.

Promising recent developments in material science, material processing and device design enable today the scientific and industrial community to concentrate efforts in the development of such kinds of "pseudo-muscular" actuators (or "artificial muscles"), by using the so-called ElectroActive Polymers (EAP), able to show electrically-induced deformations. These polymers show interesting properties, such as sizable active strains and/or stresses in response to an electrical stimulus, low specific gravity, high grade of processability and down-scalability and, in most cases, low costs.

EAP materials can be classified in two major categories:

- i) ionic EAP (activated by an electrically-induced transport of ions or molecules):
 - polyelectrolyte gels;
 - ion polymer metal composites;
 - conducting polymers;
 - carbon nanotubes;
- ii) electronic EAP (activated by an external electric field and by Coulombian forces):
 - piezoelectric polymers;
 - electrostrictive polymers;
 - dielectric elastomers.

Ionic EAPs can be activated advantageously by very low voltages (order of 1 V), but can be operated only within a surrounding electrolyte medium. Differently, electronic EAPs require typically high driving electric field (order of 10-100 V/ μ m), even though several progresses concerning the reduction of the necessary field are currently occurring.

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.

2.1 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 to the gel its typical compactness. Gels are wet and soft and look like a solid polymer material, but are capable of undergoing large deformations.

Polymer gels can be easily deformed by external stimuli, and generate force or execute work externally. 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. [1-3].

It has recently been demonstrated that water-swollen polymer hydrogels with molecularly ordered structure can be obtained by copolymerizing hydrophilic monomer such as acrylic acid with hydrophobic monomer with relatively long alkyl moiety such as stearyl acid.

These gels undergo reversible order-disorder transitions, with change in temperature, pH and solvent properties. For example gels can be used to construct a thermo-responsive diaphragm capable of automatically opening and closing a valve. The system is based on two specific properties of the polymer gels. One is the hard plastic nature below glass transition temperature and the other is that of the rubber-like soft elastomer with shape memory function [4].

If a water-swollen cross-linked polyelectrolyte gel is inserted between a pair of planar electrodes and a d.c. voltage is applied, it undergoes anisotropic contraction and concomitant fluid exudation.

The electrically induced contraction of the gel is caused by a transport of hydrated ions and water in the network (electrokinetic phenomena). When an outer electrical field is applied across the gel, both the macro- and the microions are subject to electrical forces in opposite direction. However, the macroions are a stationary phase, since they are chemically fixed to the polymer network, while the counter ions are mobile, capable of migrating along the electric field and dragging water molecules with them.

By using this phenomenon, several active devices can be realized:

- an electrically activated valve membrane, which reversibly expands and contracts its pore size in response to an electrical stimulus.
- a gel-looper: causing a pH variation by electrolysis between the two faces of a gel strip, it is possible to induce a different dilatation along the thickness of the material.

References of this Section:

- [1] Kuhn W., *Experimentia*, v. 5 (1949), 318
- [2] Breitenbach JW., Karlinger H., *Monatsh Chem*, v. 80 (1949), 211
- [3] Tanaka Y., Kagamo Y., Matsuda A., Osada Y., *Macromolecules*, v. 28 (1995), 2574.
- [4] De Rossi D., Kajivira K., Osada Y., Yamauchi A. (eds), *Polymer gels*, Plenum Press-New York (1991).

2.2 Ion-Polymer Metal Composites

Ion-polymer metal composites (IPMC) are actuators that show large deformations in presence of low applied voltages and exhibit low electrical and mechanical impedance. They operate best in a humid environment and can be made as encapsulated actuators to operate in dry conditions.

These materials have many ionizable groups in their molecular chain. These ionizable groups can be dissociated in various solvents, showing a resulting net charge, which is compensated by the presence of counterions [1].

The essence of the electromechanochemical deformations shown by IPMC 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 [2].

For a solvent such as water the local swelling and deswelling of the membrane can be controlled, depending on polarity of the nearby electrode.

This can be achieved by plating of conductive materials on membrane surfaces. Platinum is one kind of conductor that can be deposited to realize an IPMC actuator.

A typical IPMC used in the tests is Nafion-117 (Du Pont) film, i.e. a perfluorinated ion exchange membrane (IEM), on which platinum electrodes on both its sides are deposited. The thickness of the actuator is typically of the order of 0.20 mm.

To maintain the actuation capability, the film needs to be kept moist continuously.

Structure and properties of the Nafion membranes have been subjected to numerous investigations [3]. One of the interesting properties of this material is its ability to absorb large amounts of polar solvents, i.e. water. Platinum ions, which are dispersed throughout the hydrophilic regions of the polymer, are subsequently reduced to the corresponding metal atoms. When equilibrated with aqueous solutions, these membranes are swollen and they contain a certain amount of water. Swelling equilibrium results from the balance between the elastic recoil force of the polymeric matrix and the water affinity to the fixed ion exchanging sites and the moving counterions. The water content depends not only on the hydrophilic properties of the ionic species inside the membranes, but also on the electrolyte concentration of the external solution.

References of this Section:

- [1] Alexanderowica A, Katchalsky A, *J. Polymer Sci.*, v. 1A (1963), 3231
- [2] Shahinpoor M, *Proceedings of the 1993 SPIE Conference on Smart Structures and Materials*, Feb. 1-4, Albuquerque, v. 916 (1993), 40
- [3] Katchalsky A, *Experientia*, v. VI (1949), 319

2.3 Conducting Polymers

Electron conducting polymer (CP) actuators are one of the most significant entries in the class of materials for direct drive actuators, owing to their large active stresses (tens of MPa and more) and low electrical potential difference required (few Volts). In addition, an

important advantage in using CP is the possibility to fabricate actuators in different shapes (films, fibers) matching material properties with desired performances.

There are two distinct steps within the realization of a CP actuator: the optimization of the material and the fabrication of the device. In the first step we can choose the monomer and the doping ion; this strongly affects mechanical and electrical properties. Another important point is the proper choice of the electrolyte; this can be a solid electrolyte with a doping salt dissolved in it.

The second step is the fabrication of the device in an appropriate geometry; the device must consist of at least three elements: the conducting polymer (film or fiber), the electrolyte (possibly in solid state) and the counter electrode (eventually another CP). Since studies on CP are quite recent, technologies for fabricating CP actuators are at an early stage.

In conducting polymers the energetic transduction comes from the doping process in the polymeric chain. Indeed, oxidation of the polymer chain changes its bound charge and intercalation (or deintercalation) of doping ions occurs, causing structural and dimensional changes of the material to restore electroneutrality. To these phenomena noticeable changes in mechanical properties are associated and the control variable of a CP actuator is the exchanged ionic charge between the polymer and the surrounding.

It is important to underline that if the electrolyte provides negligible self-discharge and the polymer does not show mechanical creep, a conducting polymer actuator can be maintained in a specified mechanical state without consuming energy.

At least three elements are required for a CP actuator: an anode, a cathode and an electrolyte between them. There are two possible functional configurations [1]:

- electrolyte storage
- electrode storage

In the electrolyte storage configuration two different conducting polymers are used: 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.

In a periodic electrochemical stimulation, two phases are highlighted:

- during a semicycle both polymers are doped with ions from the electrolyte and they expand their volume.
- in the other semicycle both electrodes are dedoped 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 ionic conductivity between them. The polymers work alternatively as dopant storage electrodes.

In a periodic stimulation two phases are again highlighted:

- in one semicycle a polymer is doped, while the other one is dedoped; so an electrode shrinks and the other elongates. The structure bends in the direction of the shrunk electrode.
- in the second part of the cycle the roles of electrodes are exchanged and a bending occurs in the opposite direction.

If one of the two films is much thinner than the other, the structure shows elongation and not bending.

The electrolyte storage configuration leads to a linear actuator, while the electrode storage implements a bending actuator. In the second one the electrolyte quantity can be minimized (it must just provide conduction and not storage of ions). To investigate the intrinsic electromechanical properties of conducting polymers, it is preferable to use a configuration (free-standing configuration) with the conducting polymer sample immersed in a liquid electrolyte, to avoid the interference of interfacial stresses between the CP and the solid electrolyte. In this case, the actuator is the working electrode of an electrolytic cell; an inert counter electrode is used (gold or platinum) and a reference electrode is instrumental in controlling the potential through a potentiostat.

In this configuration, the polymer is able to modify its mechanic properties and active forces and displacements of the working electrode are measured.

Another commonly used configuration is the bending bilayer: a conducting polymer film is cast on a thin inert film (usually polyimide), sputtered with a gold electrode; elongation of the polymer causes bending of the structure. In this case polymer dimensional variations can not be directly quantified, but just indirectly calculated from the bending degree.

The deformation is amplified by the structure and, with a proper choice of thickness and stiffness of the substrate, the degree of bending can be quite large.

Relevant measurements concern isotonic strain and isometric stress occurring during electromechanical stimulation (triangular and square wave potential or current waves).

In isotonic conditions (under constant external force, typically zero-load) the actuation strain (at frequency f) is defined as the peak to peak value of the periodic strain.

In isometric conditions (under constant length), the force generated by the actuator is also periodic and the actuation stress (at frequency f) is defined as the peak to peak value of the periodic force, normalized per unit cross section of the sample.

Active strain of the order of 1% and active stresses of several tens of MPa are possible.

Under quasi-equilibrium conditions, the actuation strain is proportional to the exchanged charge density and the proportionality coefficient is called electrochemical strain coefficient. It can be considered a merit coefficient for a material transducing electrochemical energy into mechanical energy. There is also a limiting value of the exchanged charge density, over which actuation performances are saturated and the device has a shorter life.

Since electrochemical doping and dedoping are not completely reversible, cycle life time will also limit applicability of conducting polymer actuators. However, conducting polymer electrochemical displays have shown to be viable up to 106 cycles [2, 3].

Another important parameter is the conversion efficiency from electrical to mechanical energy. This value can be high for slow processes; since high response rates are usually required, low efficiency is expected for a CP actuator.

Conducting polymer actuators are quite simple to construct if the goal is to illustrate rather than optimize their functioning.

The first device was described by Baughman [4]. The electrochemically driven element was a film strip of a copolymer of 3-methylthiophene and 3-n-octylthiophene, sputtered on one side with gold. This element and a spatially separated lithium counter electrode were immersed in LiClO₄/propylene carbonate solution. Electrochemical reversible doping of the

polymer with ClO₄⁻ produced an expansion of the electrode and bending of the unimorph actuator.

Baughman reported then other possibilities [1, 5] to realize different actuators, such as devices for controlling fluid flow, tweezers, a CP actuator for the planar positioning of optical fibers or a Bourdon-type tube electromechanical actuator.

Cantilevers, finger-like actuators, fibers and other actuators have been proposed by several authors. Fig. 2.3.1 shows the schematic drawing of a fiber actuator developed by the Research Centre "E. Piaggio".

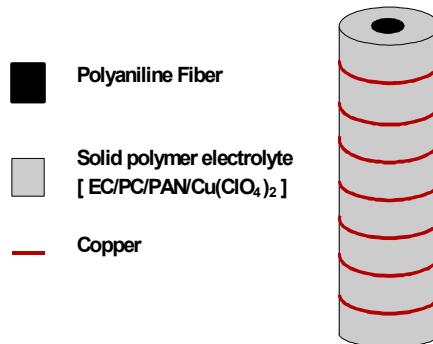


Fig. 2.3.1. Dry linear actuator based on conducting polymer

Regarding these structures, several works can be referred. Pei and Inganás [6, 7] have demonstrated the operation in solution of unimorphs, consisting of either polypyrrole/Au/polyethylene, poly(3-octylthiophene)/polypyrrole or poly(3-octylthiophene)/polyethylene sandwiches. Device response time was long, of the order of minutes, and actuator failure eventually occurred by delamination.

Otero et al. [8, 9] demonstrated similar unimorph cantilever devices, consisting of polypyrrole laminated with insulating polymer films immersed in solution.

Important developments were obtained utilizing photoresist techniques.

Smela et al. [10, 11] provided a major advance in the fabrication of cantilever-type unimorph conducting polymer actuators by using a silicon microfabrication technology. Finger-like microactuators (0.5 mm wide and 1.5 to 4 mm long) were realized with polypyrrole film (7500 Å thick) on a 3000 Å gold layer. These microactuators operated through several thousand cycles in solution before failure by delamination.

By using the same technologies, they fabricated [12] a microscopic hinged structure that reversibly assembles and disassembles from a flat array into a cube. The hinges (300x300 µm) were conducting polymer unimorph cantilevers. The actuator and the separated counter electrode worked in an electrolyte solution. Actuator response time was shorter than a second.

Lee et al [13] fabricated microcantilever unimorph actuators that operated at a frequency of 1.2 Hz for a week to perform about 5×10^5 cycles. These actuators consisted of a sandwich of polypyrrole, a very thin metal layer and an electromechanical inactive polyimide (PI) layer for mechanical support. These elements were 200-500 µm long and 50-100 µm large.

Kaneto et al. [14] gave interesting examples of bimorph conducting polymer actuators. In one of their cantilever devices, anode and cathode films of polyaniline deposited on the opposite sides of an adhesive polymer tape operated as a bidirectional bending element. When immersed in HCl 1 M, this actuator operated at frequencies above 44 Hz. An actuator operating in air was also described. It consists in a paper wetted with HCl, or a solid polymer electrolyte inserted between two polyaniline electrodes.

A similar work was reported by Takashima [15], using a polyaniline/solid polymer electrolyte/polyaniline laminated structure made of cast films from soluble emeraldine.

Wet and dry actuators based on conducting polymers have been proposed also by De Rossi group [16, 17]. In particular they proposed a new actuator constituted by a polyaniline fiber, covered by a solid polymer electrolyte and using a copper wire as counter electrode.

The same group proposed useful models to describe the passive and active behavior of this kind of polymers [18, 19].

After this initial phase, dedicated to show the possibility to obtain actuation from the conducting polymer, in the last years several works have been addressed to try to increase performances of the devices. In this context two main ways have been followed: modification of the preparation and stimulation conditions from one side, and development of devices able to amplify the actuator responses from the other side.

Smela et al. focused their attention on little samples on polypyrrole doped with dodecylbenzenesulfonate. They observed that the volume change was strongly anisotropic [20]. In fact it increases over 35% in the reduced state, compared to the oxidized state, in the direction perpendicular to the plane of the substrate but by much less parallel to the substrate.

John Madden et. al. [21, 22] applied short duration pulses of unusually high potentials, resulting in increased strain rate and power to mass ratio achievable from polypyrrole actuators of a given thickness. Most of the potential drops initially across the solution and not at polymer/electrolyte interface, explaining why there is no rapid polymer degradation at short times, despite the high potentials used.

Wen Lu et al. [23] addressed the research toward new surrounding media in order to find stimulation conditions adapt to increases the conducting polymer performances. In this context they found new solvents (liquid electrolytes as namely 1-butyl-3-methyl imidazolium cation (BMIM⁺) and either the tetrafluoroborate (BF₄⁻) or hexafluorophosphate (PF₆⁻) anions) able to avoid parasite reactions. This property is maintained within large stimulation ranges, so higher voltages can be applied and so an higher strain is possible.

Concerning devices, Ritzmaurice reports details on research of Mattes and others on polyaniline fibers [24]. The studied actuators were a 10 mm long microfibre made of 20 polymer filaments twisted together and immersed in the previously described liquid electrolyte. They found that the fibres change dimensions without any apparent degradation in performances.

Within this context of devices, De Rossi et al. proposed a technical solution to try to transform the high transversal deformation of conducting polymers in axial deformation [25]. Interesting amplified longitudinal strains could be in fact reached with a mechanical

amplification of strain, by means of a Mc Kibben-like configuration, which is able to convert and mechanically amplify a radial expansion into the longitudinal direction. Fig. 2.3.2 shows the principle of operation of such a configuration: a bundle of L_f -long CP fibers is covered by a cylindrical braid mesh (made with flexible, but not extensible threads), subjected to a constant load F and able to contract when the internal elements exert a radial expansion: the system undergoes an increase of its diameter (D_{m1} into D_{m2}) and of the angle between the longitudinal axes and the threads (α_1 into α_2), causing the decrease of its length (L_{m1} into L_{m2}).

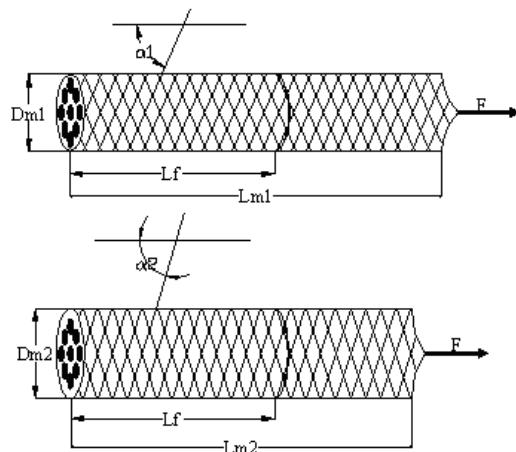


Fig. 2.3.2. Schematic drawing of a Mc Kibben-like actuating configuration

References of this Section:

- [1] Baughman R.H., Synth. Met., v. 78 (1996), 339.
- [2] Kobayashi Y., Yonegama H., Tamura H., J. Electroanal. Chem., v. 161 (1984) 419.
- [3] Foot P.J.S., Simon J., J. Phys D: Appl. Phys., v. 22 (1989), 1589
- [4] Baughman R.H., Schacklette, L.W., Science and Applications of conducting polymers, Salaneck W.R., Clark D.T., Samuels E.J. (eds), Adam Hilger, Bristol-Philadelphia- New York, (1990), 47
- [5] Baughman, R.H., Schacklette L.W., Elsenbaumer R.L., Plichta E., Becht C., Conjugated Polymeric Materials: Opportunities in Electronics, Optoelectronics and Molecular Electronics, Bredas J.L. and Chance R.R (eds), Kluwer Academic Publ., (1990), 559
- [6] Pei Q., Inganás O., Adv. Mater., v. 4 (1992), 277
- [7] Pei Q., Inganás O., Synth. Met., v. 55-57 (1993), 3718
- [8] Otero T.F., Rodriguez J., Angulo E., Santamaria C., J. Electroanal. Chem., v. 341 (1992), 369
- [9] Otero T.F., Rodriguez J., Angulo E., Santamaria C., Synth Met., v.55-57 (1993), 3717
- [10] Smela E., Inganás O., Pei Q., Lundstrom I., Adv. Mater., v. 5 (1993), 630
- [11] Smela E., Inganás O., Lundstrom I., J. Micromech. Microeng., v. 3 (1993), 203
- [12] Smela E., Inganás O., Lundstrom I., Science, v. 268 (1995), 1735
- [13] Lee A.P., Hong K.C., Trevino J., Northrop M.A., Dynamics Systems and Control, ASME Publication DSC 55-2, ASME , New York (1994), 725
- [14] Kaneto K., Kaneko M., Min Y., McDiarmid A.G., Synth. Met., v. 71 (1995) 2211.
- [15] Takashima T., Kaneto K., Kaneko M., McDiarmid A.G., Synth. Met., v. 71 (1995), 2265
- [16] Della Santa A., De Rossi D., Mazzoldi A., Tiberi M., International Symposium on Microsystems MIMR'95 (Jap.) (1995), 275

- [17] A. Mazzoldi, C. Degl'Innocenti, M. Michelucci, D. De Rossi, Materials Science & Technology C: Biomimetic Material, Sensors and Systems, v. 6 (1998), pp. 65-72
- [18] D. Della Santa, A. Mazzoldi, C. Tonci, D. De Rossi, Materials Science & Technology C: Biomimetic Material, Sensors and Systems, v. 5 (1997), 101
- [19] D. Della Santa, D. De Rossi, A. Mazzoldi, Smart Material and Structures, vol. 6 (1997), 23
- [20] E. Smela, N. Gadeguard, Adv. Mater 11 (1999), 953-957
- [21] J.D.Madden, R.A. Cush, T.S.Kanigan, I.W.Hunter, Synthetic Metals 2000, 113, 185-192.
- [22] J. N. Barisci, G. M. Spinks, G. G. Wallace, J.D.Madden and R. H. Baughman, Smart Mat. And Struct. 2003, 12, 549-555.
- [24] D. Fitzmaurice, Physics World, 09-02, 25
- [25] D. De Rossi, F. Lorusso, A. Mazzoldi, W. Rocchia, E.P. Scilingo, EAPAD-SPIE (Newport Beach, CA, Marzo, 2001).

2.4 Carbon Nanotubes

Carbon nanotubes (CNT) are the most recent addition to the class of electroactive materials. They can be described as a graphite film rolled to form a tube. Carbon nanotubes have lengths about 1000 times their width (typical diameters are about 10 Angstrom, while typical lengths about 1 micrometer) and typically they are combined in bundles of 100 Angstrom diameter. Carbon nanotubes can be divided in two classes: single-wall and multi-wall. A single-wall CNT consists in a single film rolled to make a tube, while a multi-wall CNT is made of several films rolled one on the others. Mechanical performances of multi-wall tubes are predicted to be lower, respect to those predicted for the single-wall ones, considering the lower forces between the layers.

CNT actuators [1] can be realized using sheets of single-wall nanotubes. Nanotube sheet actuators are arrays of nanotubes, as for natural muscle [2]. Unlike conducting polymers, which can act as batteries, CNT can be used as electrochemical supercapacitors [1]. A Change of the applied voltage results in a double-layer charge injection for very high surface-area electrodes. The principle of operation for actuating purposes is represented by this charge-injection, which is able to produce dimensional changes in covalently bonded directions for conjugated materials, which originate from quantum chemical and double-layer electrostatic effects.

Early investigations showed active strains of the order of 0.2%, depending on the experimental conditions, when the applied voltage was limited to the electrochemical stability of the electrolytes.

Recently, we have made and characterised nanotube thin fibers in collaboration with University of Texas at Dallas and other research groups. The apparently superior mechanical and electrical properties (generated stresses, low driving voltages, high energy densities) of these materials (conducting polymers and carbon nanotubes) suggest that we can expect high potential actuating performances [3]. Nevertheless, presently their development requires many additional efforts to enable their use as biomimetic actuators.

References of this Section:

- [1] R.H. Baughman, Changxing Cui, A.A. Zakhidov, Z. Iqbal, J.N. Barisci, G.M. Spinks, G.G. Wallace, A. Mazzoldi, D. De Rossi, A.G. Rinzler, O. Jaschinski, S. Roth, M. Kertesz, *Science*, v. 284 (1999), 1340.
- [2] J.A. Spudich, *Nature*, 372 (1994), 515.

[3] G.M. Spinks, G.G. Wallace, L.S. Fifield, L.R. Dalton, A. Mazzoldi, D. De Rossi, I.I. Khayrullin, R.H. Baughman, "Pneumatic carbon nanotube actuators", Advanced Materials, vol 14, issue 23 (2002), 1728-1732.

2.5 Electrostrictive Polymers

Electrostriction is the main electro-mechanical coupling phenomenon shown by any dielectric material. It consists of a quadratic dependence of the strain and stress on the material polarization, due to an applied electric field. For materials showing a linear relation between polarization and applied electric field (E), the electrostrictive strain (or stress) depends on the square of E : $\text{Strain} = QE^2$.

Although any dielectric polymer is electrostrictive, this property is commonly attributed only to those polymers manifesting markedly this effect. In fact, most of polymers present a relatively low degree of electrostriction, mainly due to the low value of their dielectric permittivity.

Ferroelectric polymers are also piezoelectric and pyroelectric and present typically a semi-crystalline molecular structure (crystals immersed in an amorphous matrix). Most notable examples of such kind of materials are poly(vinylidene fluoride) (P(VDF)) and its copolymers with trifluoroethylene (P(VDF-TrFE)), with tetrafluoroethylene (P(VDF-TFE)) and with esafluoropropylene (P(VDF-HFP)).

Ferroelectric polymers have an elastic modulus of the order of 1-10 GPa. By applying an AC high electric field (order of 100 V/ μm), strains of the order of 1% can be obtained; hysteresis effects can occur within the operative range [1,2].

Moreover, recent investigations showed that a drastic reduction of the driving electric fields of electrostrictive polymers can be obtained by mixing with the polymer matrix an highly dielectric component. In particular, composite materials realized by using P(VDF-TrFE) as polymeric matrix and copper-phthalocyanine (CuPc), as organic filler with high dielectric permittivity, showed 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 [3].

Actuators realized with electrostrictive ferroelectric EAP can be operated in air, water or vacuum and in a wide range of temperature. Since these polymers are piezoelectric too, they can be used as both actuators or sensors. In fact, a stress applied to the material induces electrical charges on the material surfaces, generating a useful voltage signal.

References of this Section:

- [1] Q. M. Zhang, V. Bharti, X. Zhao, "Giant electrostriction and relaxor ferroelectric behaviour in electron-irradiated poly(vinylidene fluoride-trifluoroethylene) copolymer", Science 280 (1998) 2101-2103.
- [2] Y. Cheng, V. Bharti, T.-B. Xu, Haisheng Xu, T. Mai, Q.M. Zhang, "Electrostrictive poly(vinylidene fluoride-trifluoroethylene) copolymers", Sensors and Actuators A 90 (2001) 138-147.
- [3] Q. M. Zhang, H. Li, M. Poh, F. Xia, Z.-Y. Cheng, H. Xu & C. Huang, "An all-organic composite actuator with a high dielectric constant", Nature 419 (2002) 284-287.

2.6 Dielectric Elastomer Actuators

Dielectric polymers having a low elastic modulus and subjected to an high electric field exhibit large deformations mainly due to a Coulombian effect, that is by means of the

electrostatic interactions among the free charges on the electrodes. When a thin film of such materials is sandwiched between two compliant electrodes (e.g. made of carbon conductive grease) and a voltage difference is applied between them, the polymer undergoes an electric field-sustained deformation, consisting of a thickness squeezing and a surface expansion (Fig. 2.6.1) [1-4].

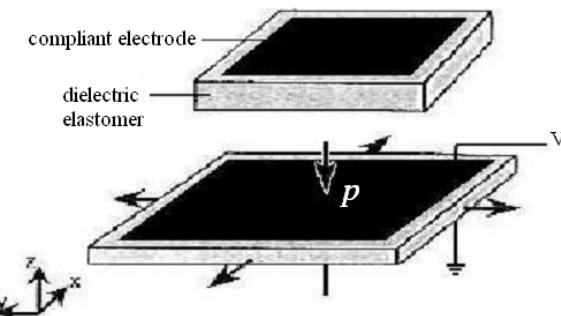


Fig. 2.6.1. Principle of operation of a dielectric elastomer planar actuator

Acrylic elastomers and silicone elastomers are the most representative materials of this EAP class. Such kinds of polymers are very compliant and have shown the highest actuating deformations among all EAP materials. Assuming a dielectric elastomer as a linearly elastic body, having a Young's modulus Y and a relative dielectric constant ϵ_r , subjected to an electric field E , linear strains (S) along the electric field direction can be described by the following equation [1-4]:

$$S = -\frac{1}{Y} \epsilon_0 \epsilon_r E^2 \quad (2.6.1)$$

where ϵ_0 is the free-space dielectric permittivity ($\epsilon_0 = 8.85 \times 10^{-12}$ F/m). The quadratic dependence of the strain on the applied field predicted by the previous equation is shown by the example of Fig. 2.6.2.

Acrylic polymers (or acrylates) are soft and highly viscoelastic materials which can exhibit high-level actuating capabilities: thickness strains up to 60-70 % at 400 V/ μ m, area strains (Fig. 2.6.3) up to 200 % at 200 V/ μ m and corresponding stresses of some MPa [4]. Such performances are enabled by their low elastic modulus and high dielectric strength (dielectric breakdown occurs at electric fields of about 500 V/ μ m). Material prestretching, before the application of the electric field, was demonstrated to increase active performances, due to the increase of the polymer elasticity and dielectric strength [4].

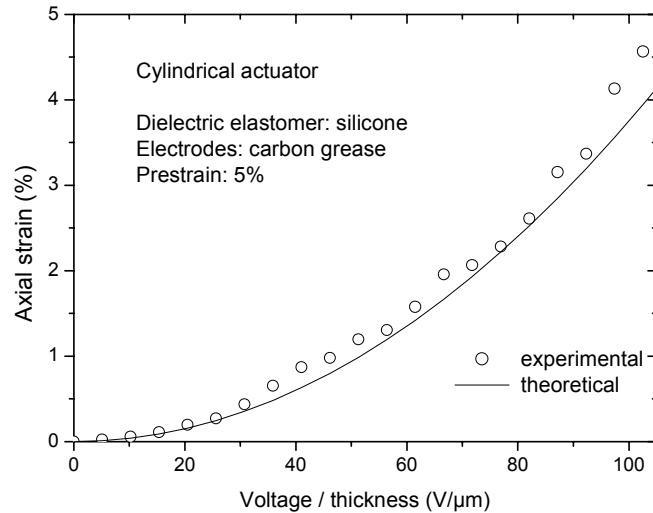


Fig. 2.6.2. Strain of a silicone cylindrical actuator realized at the Research Centre "E. Piaggio" (adapted from [7]).

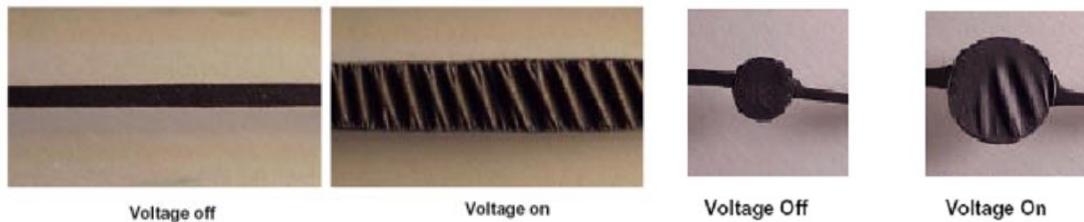


Fig. 2.6.3. Images showing electrically-activated electrode expansions for an acrylic elastomer (adapted from [4]).

Silicone elastomers are easily processable (by spin coating, casting,...) amorphous polymers which permit the realization of good elastomers, owing to the high mobility of the Si-O bonds, which confer high flexibility to main chains. Dielectric breakdown of silicones occurs at electric fields ranging from 100 to 350 V/μm, enabling thickness strains up to 40-50% and area strains up to 100% with related stresses of 0.3-0.4 MPa [4].

The excellent figures of merit possessed by dielectric elastomers in several respects (high actuation strains and stresses, fast response times, high efficiency, stability, reliability and durability) make them the most performing materials currently available for polymer actuation. The price for achieving these high-level capabilities is represented by the high driving electric fields needed (order of 100 V/μm). For a definite polymer thickness, such field levels can be reached by using high voltages, which may be disadvantageous in many applications. For this reason, in order to reduce the driving electric fields, polymers with high dielectric constant are necessary (Eq. (2.6.1)).

With respect to this, new highly dielectric elastomers can be realized by means of a composite approach. By filling an ordinary elastomer (e.g. silicone) 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. On this regard, Fig. 2.6.4 shows preliminary results, obtained at the Research Centre “E. Piaggio”, concerning the active deformations of a silicone elastomer (relative permittivity of about 5) mixed with titanium dioxide (relative permittivity of about 114).

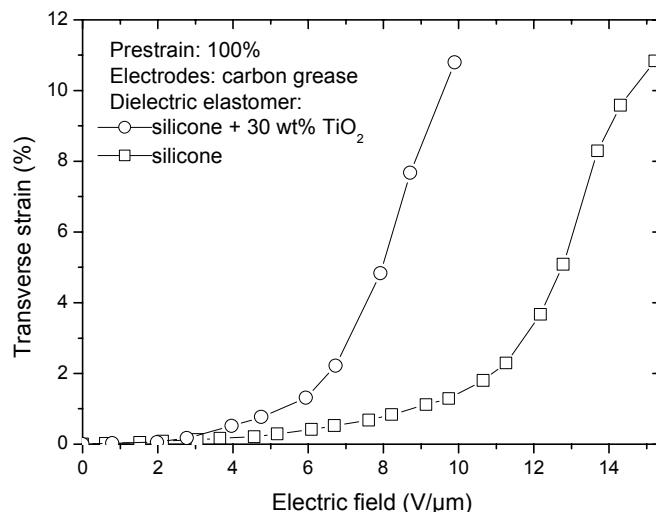


Fig. 2.6.4. Strain-electric field curves of planar actuators made of a silicone elastomer and by the same material loaded with a 30 wt% titanium dioxide (TiO_2) powder (data from the Research Centre “E. Piaggio”).

So far, many actuating configurations have been proposed and demonstrated, including planar, tube, rolled, extender, diaphragm, bimorph and unimorph bender (Fig. 2.6.5) [1-7].

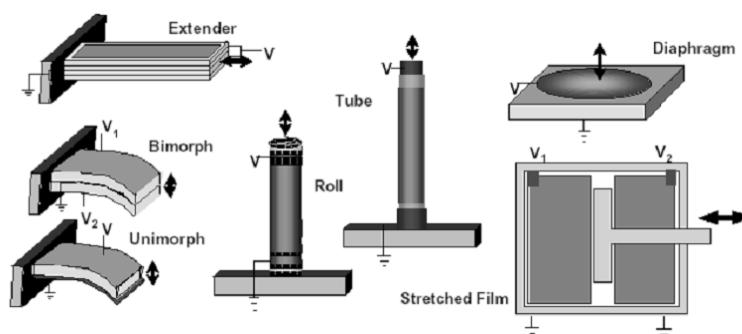


Fig. 2.6.5. Existing configurations for dielectric elastomer actuators

A new configuration for dielectric elastomer actuators recently developed by the Research Centre “E. Piaggio” will be described in Section 3, as well as its potential usefulness for the application of interest in this study.

References of this Section:

- [1] R. E. Pelrine, R. D. Kornbluh and J. P. Joseph, Electrostriction of polymer dielectrics with compliant electrodes as a means of actuation, Sensors and Actuators A 64 (1998) 77-85.
- [2] R. Pelrine, R. Kornbluh and G. Kofod, “High-strain actuator materials based on dielectric elastomers”, Adv. Mater, Vol. 12 n°16 (2000), 1223-1225.
- [3] R. Pelrine, R. Kornbluh, J. Joseph, R. Heydt, Q. Pei, S. Chiba, High-field deformation of elastomeric dielectrics for actuators, Materials Science and Engineering C 11 (2000) 89-100.
- [4] R. Pelrine, R. Kornbluh, Q. Pei and J. Joseph, High-speed electrically actuated elastomers with strain greater than 100%, Science 287 (2000) 836-839.
- [5] Q. Pei, R. Pelrine, S. Stanford, R. Kornbluh, M. Rosenthal, Electroelastomer rolls and their application for biomimetic walking robots, Synthetic Metals 135-136 (2003) 129-131.
- [6] F. Carpi, P. Chiarelli, A. Mazzoldi, D. De Rossi, Electromechanical characterisation of dielectric elastomer planar actuators: comparative evaluation of different electrode materials and different counterloads, Sensors and Actuators A 107 (2003) 85-95.
- [7] F. Carpi, D. De Rossi, “Dielectric elastomer cylindrical actuators: electromechanical modelling and experimental evaluation”, Materials Science and Engineering C, vol. 24(4) pp. 555-562, 2004.

2.7 Comparison Among The Different EAP Materials

Tab. 2.7.1 provides a final summary of the advantages and disadvantages of the various EAP materials described so far. This table can be used as an operative guide for the choice of the best type of materials suitable for the application of interest.

Tab. 2.7.1. Advantages and disadvantages of EAP actuating materials.

EAP materials	Advantages	Disadvantages
Polyelectrolyte gels	-high strains -low driving voltages	-low stresses -high response time -low reliability and lifetime
Ion polymer metal composites	-high strains -low driving voltages	-low stresses -high response time. -low reliability and lifetime
Conducting polymers	-high stresses -low driving voltages	-low strains -high response time -low efficiency, reliability and lifetime
Carbon nanotubes	-high stresses (expected) -low driving voltages	-low strains -medium response time -low reliability and lifetime -expensive and difficult to process
Electrostrictive polymers	-high stresses -low response time -high efficiency, reliability and lifetime	-low strains -high driving voltages
Dielectric elastomers	-high strains -high stresses -low response time -high efficiency, reliability and lifetime	-high driving voltages

3. Identification of suitable EAP materials and configuration for the application

The comparison of the actuating properties exhibited by the considered different classes of EAPs (Section 2) demonstrate how the attractive properties of dielectric elastomers are responsible of the growing tendency to view them as one of the most promising classes of materials for many actuation tasks, owing to their high active strains, stresses, response times, stability, durability and reliability.

In particular, such actuating superiority of dielectric elastomers leads to consider them as elected candidate materials for the development of the actuation mechanism of the "Mars jumping rover".

As presented above, so far several configurations for dielectric elastomer actuators have been proposed, demonstrated and studied, including planar, tube, roll, extender, diaphragm, bender. Owing to their linear (along a line) actuation capabilities, tube and, mainly, roll actuators are potential candidates for the realisation of "*artificial muscles*". However, they present a mechanism of actuation opposite to that of natural muscles: under electrical stimulation they elongate, instead of contract. In order to overcome this limitation, actuators able to undergo electrically-activated contractions are demanded. On this regard, the Research Centre "E. Piaggio" has recently developed a new actuating configuration, described below.

The new configuration is based on a structure designed more generally for EAP devices and recently patented and presented [1-3]. It consists of a hollow cylinder of dielectric elastomer, having two helical compliant electrodes integrated within its wall, so that to result continuously alternated to the dielectric material. By applying a voltage difference between the electrodes, the interactions among their free charges cause axial contractions of the actuator, as well as related radial expansions (Fig. 3.1).

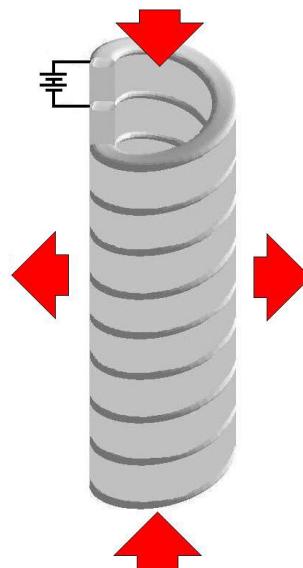


Fig. 3.1 A new dielectric elastomer linear actuator.

Therefore, devices based on this actuation scheme may be regarded as electrically activated polymer springs.

By assuming that the elastomer is a linearly elastic body and that the applied electric field E is approximately uniformly distributed inside it, it can be demonstrated that the axial strain generated in this configuration is described by this relation:

$$\text{Axial Strain} = \frac{\epsilon_0 \epsilon_r E^2}{Y} (\cos \alpha - \sin \alpha) \quad (3.1)$$

where ϵ_0 is the dielectric permittivity of vacuum, ϵ_r is the relative dielectric constant of the material, Y is its elastic modulus and α is the angle of inclination of each electrode with respect to the device axis.

The first silicone-made prototypes realised so far have an external diameter of 1 cm and a length lower than 10 cm (Fig. 3.2). However, the fabrication of actuators with larger dimensions, as required by the application of interested (see Section 4), in principle would not modify the performances of the device.



Fig. 3.2 Photograph of a prototype of the new kind of actuator.

Fig. 3.3 shows results of a preliminary characterisation of the linear electromechanical contraction performances of the first prototypes. In particular, this figure reports axial contraction strains obtained in response to the application of the indicated electric fields.

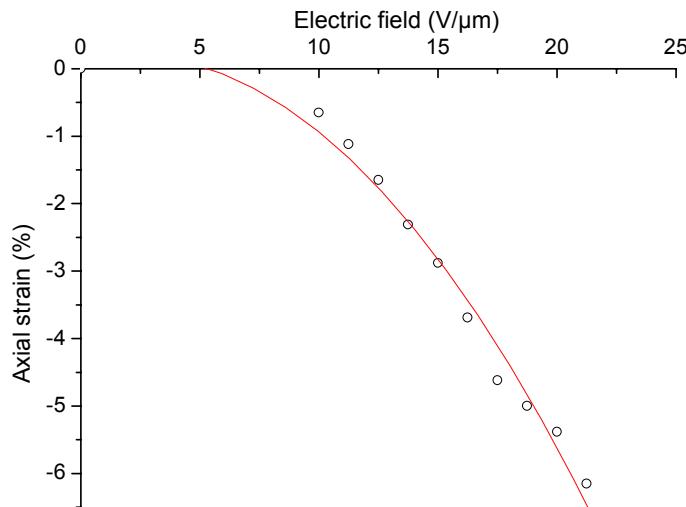


Fig. 3.3. Preliminary data on axial contraction strain versus applied electric field
 (data from the Research Centre "E. Piaggio").

These results indicate that, presently, contraction strains of about -6% at $22\text{ V}/\mu\text{m}$ are achievable. However, higher performances are expected with future developments of the fabrication process, currently under development at the Research Centre "E. Piaggio". For instance, in our opinion strains of the order of -10% at about $25\text{-}30\text{ V}/\mu\text{m}$ can be considered as a realistic near target, so that they have been assumed as a reference for the analyses developed in this study (see Section 5).

This linearly contacting dielectric elastomer actuator has been identified as suitable device for the application of interest in this study, as it is shown in the following sections.

References of this Section:

- [1] F. Carpi, D. De Rossi, "Theoretical description and fabrication of a new dielectric elastomer actuator showing linear contractions", *Proc. of Actuator 2004*, Bremen 14-16 June 2004, pp. 344-347.
- [2] F. Carpi, D. De Rossi, "Electroactive polymer contractile actuator", PCT International Application (2004), PCT/IB2004/001868.
- [3] F. Carpi, D. De Rossi, "Attuatore elettromeccanico contrattile a polimero elettroattivo con elettrodi deformabili elicoidali", *Italian Patent* (2003), PI/2003/A/000043.

4. Problem modelling and proposed solutions

The dielectric elastomer device described above and identified as suitable linear electromechanical actuator has been considered to propose two solutions to the problem of the "Mars jumping rover", as described below.

The linear actuator made of a silicone rubber and represented by an hollow cylindrical tube with outer radius R_1 and inner radius R_2 (Fig. 4.1), has been conceived as the bar capable to provide the actuating function to the sphere for its jumping. Values of its dimensions are indicated in Table 5.1 in Section 5.

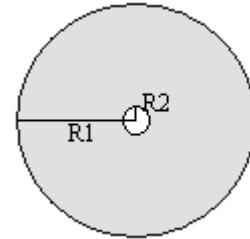


Fig. 4.1. Section of the dielectric elastomer actuator

The actuator is integrated in the host structure represented by the spherical shell (Fig. 4.2), assumed to have a radius of 1 m and a thickness of 1 mm.

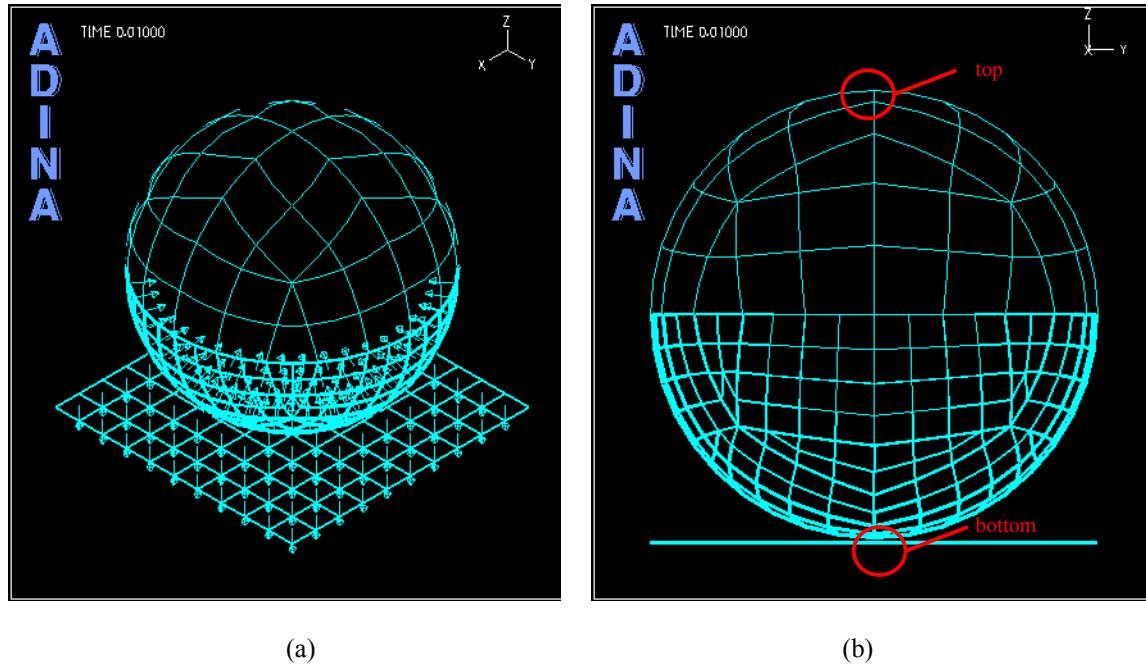


Fig. 4.2. Spherical shell working as "Mars jumping rover".

In particular, we propose the two configurations reported in Fig 4.3 ("Case A" and "Case B") and described below.

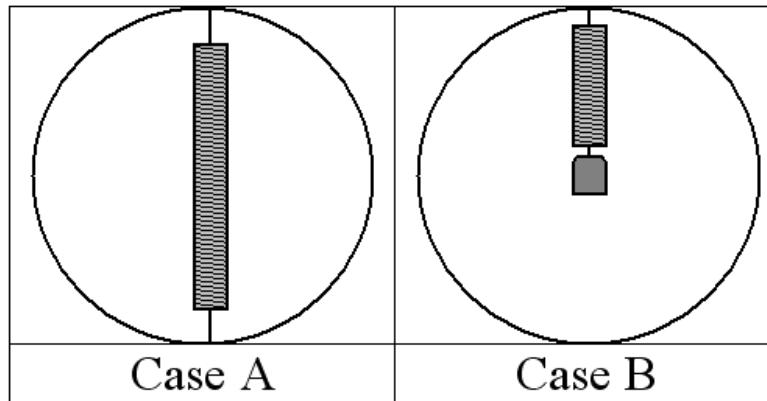


Fig. 4.3. Proposed configurations for the solution of the problem.

Case A:

in the first configuration, the contracting dielectric elastomer actuator is placed along the sphere diameter.

In principle, the application of a definite electric field to the actuator will tend to compress it, causing a deformation of the shell and, lowering the position of the center of gravity (CoG) of the system. The following release of the actuator will trigger the jumping of the sphere, by turning the stored strain energy into kinetic, and ultimately gravitational energy.

Given the assumed jump mechanism, it is of importance that the sphere be as compliant as possible; a rigid sphere would allow no jump.

Case B:

in the second configuration, a dummy mass is attached to the lower end of a 1 metre-long actuator, having its higher end connected to sphere. Therefore, the couple actuator/mass results suspended inside the sphere.

The jumping mechanism is conceived to exploit the inertia of the sphere and of the dummy mass, as well as the strain energy of the actuator. In principle, an abrupt electrical compression of the actuator will lift the mass; then, following the removal of the electric stimulus, the resulting extension of the actuator will pull the dummy mass and the sphere one away from the other: the first one will dive towards the ground, while the sphere will be lifted.

The amplitude of such an effect is expected to strongly depend on the ratio of the masses (M_{dummy} and M_{sphere}) of the two bodies:

$$M_{dummy} / M_{sphere}$$

In fact, the strain energy stored in the actuator (the amount of energy stored in the sphere is here neglected for simplicity) will be transformed into kinetic energy of the two bodies, which will receive the same variation of momentum (q):

$$\Delta q = M_{dummy} \Delta v_{dummy} = M_{sphere} \Delta v_{sphere}$$

where v_{dummy} and v_{sphere} are the velocities of the dummy mass and of the sphere, respectively. This relation shows that the higher is the mass ratio, the higher the sphere will jump.

Moreover, the considered actuator mass is not negligible (see Table 5.1 in Section 5) and, in order to calculate the mass ratio, it has to be added to the dummy mass. It also affects the position of the CoG of the dummy mass.

In case B, the elastic characteristics of the sphere are expected to play only a minor role in the jumping phase. It is envisaged that a stiff sphere will give a better performance, because the actuation will only strain the actuator itself, leaving the sphere undeformed and maximizing the increase in height of the CoG of the dummy mass.

Simulations with different values of the Young modulus of the sphere's material shall be performed, in order to investigate this role.

5. Numerical simulations: assumptions and method

In order to validate both the proposed solutions, numerical simulations have been performed, according to the following simplifying assumptions:

- No coupling has been implemented between the electrical and mechanical domains, so that deformation does not affect the electrical behaviour.
- The system has been assumed as linear with respect to its constitutive relations. Moreover, materials used for both the shell and the actuator are assumed as homogeneous and isotropic.
- The mechanical environment of the system under study has been assumed to consist only of the Mars' gravity and the reaction of the floor, modelled as a unilateral constraint (the sphere can loose contact with the floor). A contact algorithm has been implemented as described in [1].
- Assumed initial conditions: the sphere is dropped from a height of 1 mm, starting with a null velocity.
- Parameters of the shell and of the actuator assumed for the simulations: see Table 5.1.

In order to investigate the effects of the stiffness of the sphere material on the resulting performances, the different values of Young's modulus (elastic modulus) reported in Table 5.1 have been assumed for the numerical simulations. These values have been selected in consideration of the reasonably different stiffness required for the sphere by the two proposed configurations. The two values for case A have been arbitrarily selected to obtain a compliant sphere. In case B, a stiff sphere has been considered: the structure may consist, for example, of a sandwich shell with carbon fiber reinforced plastic (CFRP) skins. Also an inner pressurization can be envisaged.

Table 5.1. Assumed parameters for the simulations.

		Case A	Case B
Shell	Young's modulus	10 MPa, 100 MPa	1 GPa, 100 GPa
	Poisson's ratio	0.3	0.3
	Density	500 kg/m ³	500 kg/m ³
	Dimensions	Radius: 1 m Thickness: 0.001 m	Radius: 1 m Thickness: 0.001 m
	Mass	6.3 kg	6.3 kg
Actuator	Young's modulus	100 kPa	100 kPa
	Poisson's ratio	0.49	0.49
	Density	1000 kg/m ³	1000 kg/m ³
	Dimensions	R1= 0.05 m R2=0.005 m Length: 2 m	R1= 0.1 m R2=0.005 m Length: 1 m
	Mass	15.6 kg	31.3 kg
	Active strain (free stroke)	-10%	-10%
	Stimulation time	0.2 s	0.2 s
	Dummy mass	--	1 kg

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

The simulation of the actuation mechanism has been implemented by means of a thermal analogy: in correspondence to the maximum active strain that the actuator is able to provide, a fictitious negative coefficient of thermal expansion has been assigned to the actuator material (silicone), so that, once a unit variation of temperature is applied to it, its contraction matches the required maximum active strain, assumed as -10%. In terms of effective electrical stimulation, this strain corresponds to the application of an electric field of about 25-30 V/μm (see Section 3). The active stimulation of the actuator has been simulated with the application of step stimuli having a length of 0.2 s and a magnitude corresponding to the imposed strain of -10%.

Reference of this Section:

[1] Bathe, K.J. and Chaudhary, A., "A Solution Method for Planar and Axisymmetric Contact Problems," *Int. J. Num. Meth. in Eng.*, Vol. 21, pp. 65-88, 1985.

6. Simulation results

Case A

Fig. 6.1 presents the jumping sphere actuated via the configuration of case A.

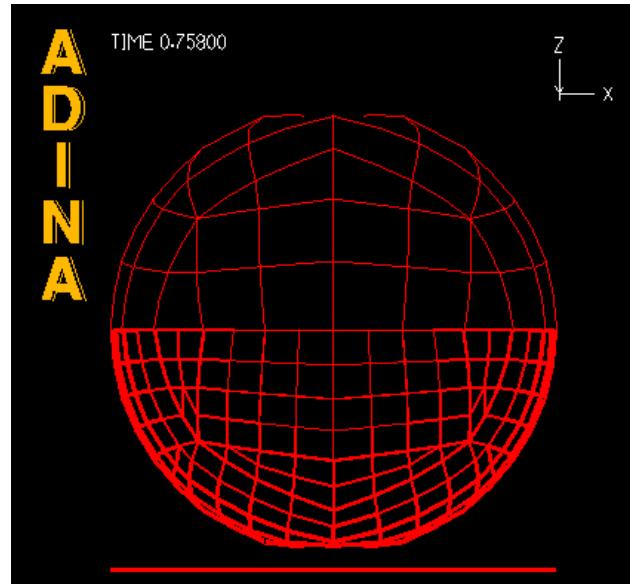


Fig. 6.1. Jump of the sphere achievable with the actuating configuration of case A.

The plots reported in Figs. 6.2 and 6.3 show, for the two considered elastic moduli of the sphere, the time dependence of the vertical (z) displacements of the (geometrical) center and bottom points of the sphere, with respect to their initial positions.

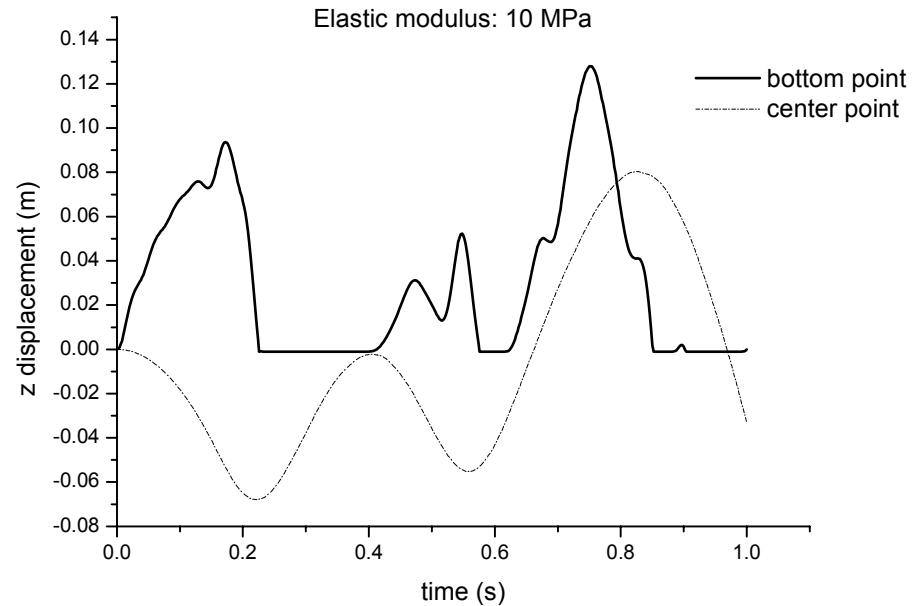


Fig. 6.2. Time dependence in case A of the displacements of the center and bottom points of the sphere (having an assumed elastic modulus of 10 MPa).

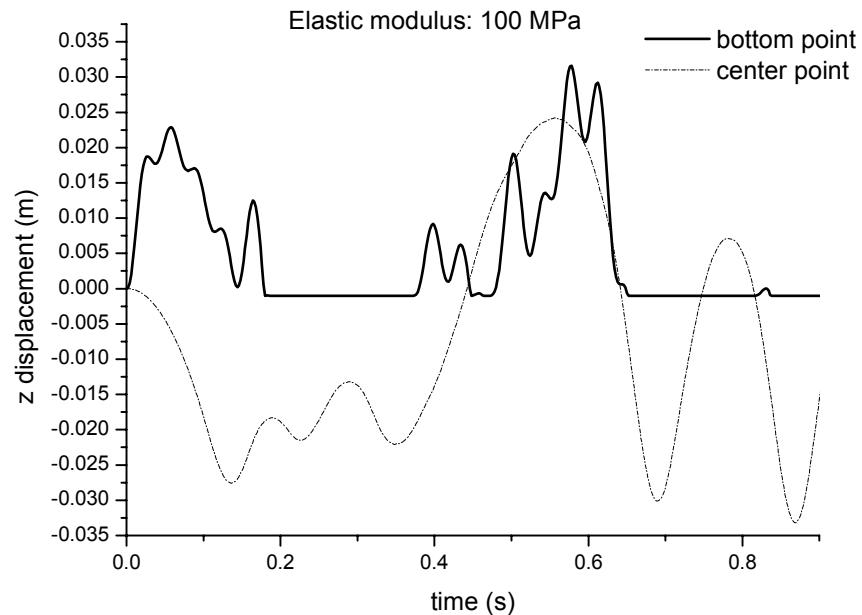


Fig. 6.3. Time dependence in case A of the displacements of the center and bottom points of the sphere (having an assumed elastic modulus of 100 MPa).

Owing to the compliance of the shell, in this configuration the top and bottom points (where the actuator is connected to the structure) undergo, during the phase of active compression of the actuator, deformations considerably higher than those shown by the other points of the sphere (Fig. 6.4)

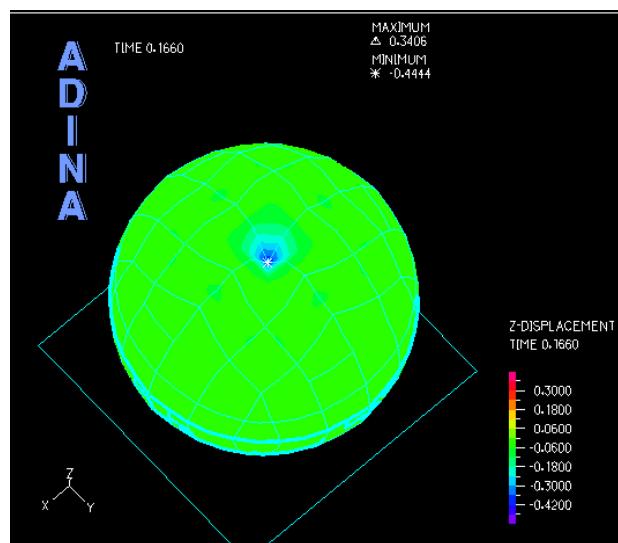


Fig. 6.4. Initial active deformation of a sphere with an elastic modulus of 10 MPa during the compression of the actuator in the configuration of case A.

Therefore, in this case the most significative variable quantifying the jumping capability of the system is represented by the displacement of the geometrical center point of the sphere. On this regard, the maximum achievable displacement of this point is listed in Table 6.1.

Table 6.1. Maximum displacement of the center point of the sphere in case A.

Elastic modulus of the sphere (MPa)	Displacement of the center point of the sphere (cm)	Ratio between displacement and rest diameter of the sphere
10	8	4%
100	2.5	1.3%

Case B

The jumping sphere actuated via the configuration of case B is presented in Fig. 6.5.

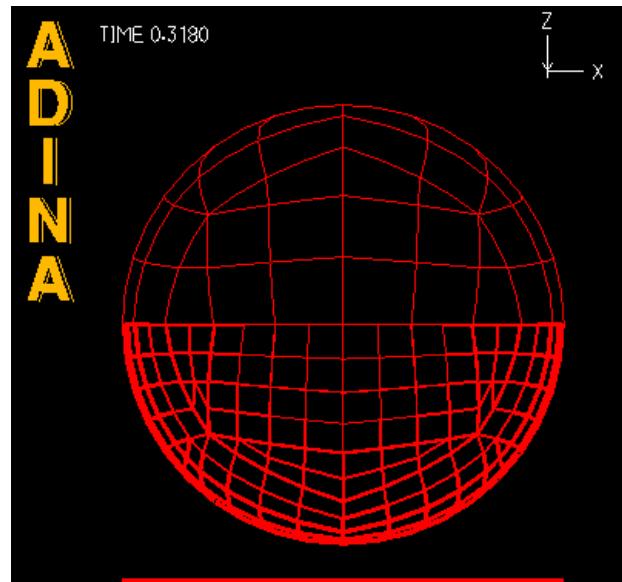


Fig. 6.5. Jump of the sphere achievable with the actuating configuration of case B.

Figs. 6.6 and 6.7 show the simulated performances of this configuration, providing the temporal displacements along the vertical (z) direction of the dummy mass and of the bottom points of the sphere, for the considered values of its elastic modulus.

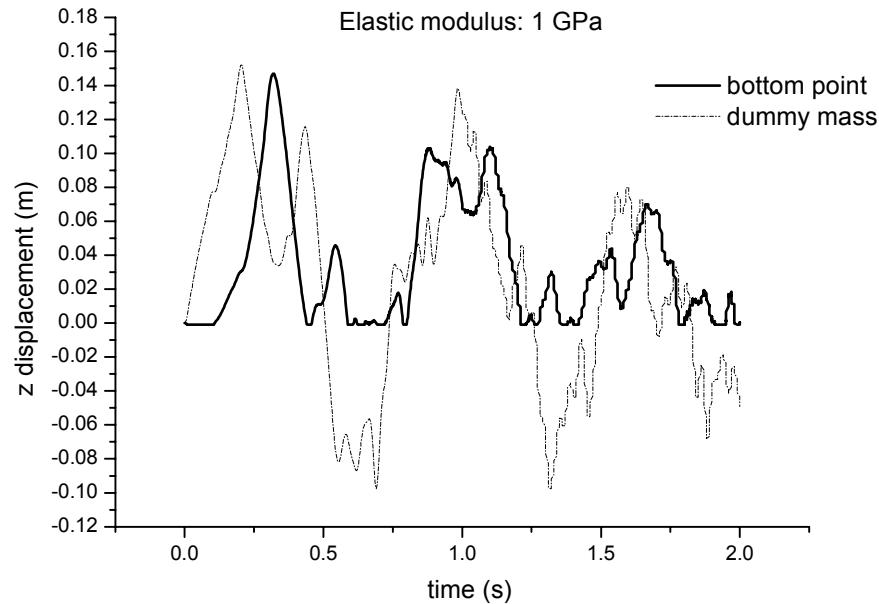


Fig. 6.6. Time dependence in case B of the displacement of the bottom point of the sphere (having an assumed elastic modulus of 1 GPa), as well as of the dummy mass.

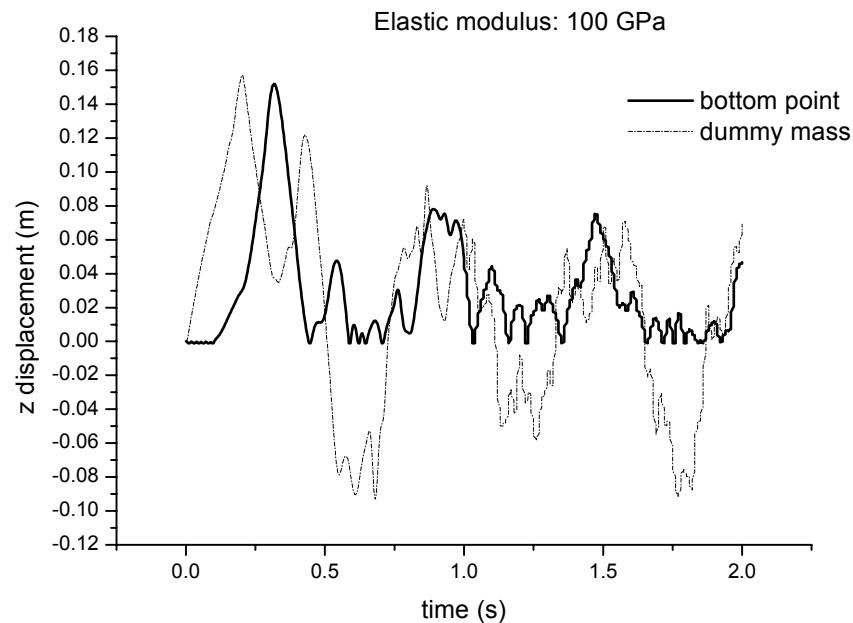


Fig. 6.7. Time dependence in case B of the displacement of the bottom point of the sphere (having an assumed elastic modulus of 100 GPa), as well as of the dummy mass.

Differently from case A, for this configuration the most significative variable quantifying the jumping capability of the system is represented by the displacement of the bottom point of the sphere. Therefore, Table 6.2 reports the maximum achievable displacement of this point.

Table 6.2. Maximum displacement of the bottom point of the sphere in case B.

Elastic modulus of the sphere (GPa)	Displacement of the bottom point of the sphere (cm)	Ratio between displacement and rest diameter of the sphere
10	14.7	7.4%
100	15.2	7.6%

Fig. 6.8 presents the Von Mises (smoothed) stress plot on the sphere. It provides an estimate of the extension of the area stressed by the actuator.

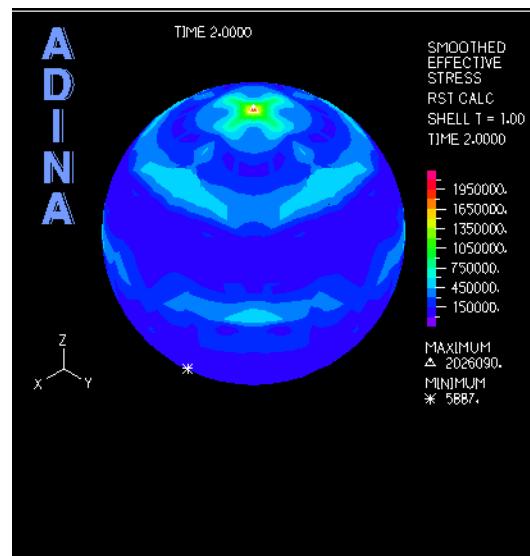


Fig. 6.8. Von Mises stress plot for the sphere in case B.

7. Discussion

In order to maximise the jumping height of the sphere, it is necessary to achieve the maximisation of the energy conversion from the electrical form into the elastic one, which is then released as kinetic energy for the jumping. The two considered configurations operate this energy transduction according to different solutions, which exploit inverse mechanical properties required to the shell, as discussed below.

Case A

In this configuration, the higher is the compliance of the sphere, the lower is its constraining action on the actuator, which, therefore, can be easily electrically strained, leading to the elastic energy accumulation. As a result, the sphere will be pushed by the actuator towards the floor and, when the actuation force is released, it will jump, converting strain energy into gravitational energy. This is confirmed by the simulation results presented in Figs. 6.2 and 6.3, which indicate that the jumping capability of the sphere increases with the compliance of the sphere.

Differently, if the sphere is too stiff, it does not strain appreciably and the actuator undergoes limited displacement (no displacement if the sphere is rigid); in this situation, the active stimulus mostly induces stress in the actuator material.

However, with a relatively compliant sphere, the actuator strains it mainly in the two zones located around the points of its connection to the sphere (as confirmed by the image shown in Fig. 6.4). Furthermore, this phenomenon is emphasized by the compliance of the shell. Therefore, the effective jumping performances enabled by this configuration are identified by the achievable displacement of the center of the sphere, rather than that of its bottom point. Fig. 6.2 reveals a maximum displacement of the center of 8 cm, corresponding to the 4% of the rest diameter of the sphere, despite a maximum displacement of the bottom point of 13 cm, representing the 6.5% of the rest diameter of the sphere.

On this regard, it is interesting to note in Fig. 6.2, for instance, that during the 0.2-second-long active contraction phase of the actuator, the bottom point is lifted, while the center point falls down. At the end of this phase, the sphere is compressed (mostly at its top and bottom points) and when the actuator is released, the center of the sphere starts to be lifted, while the bottom point does not move until the sphere completely recovers its original shape, giving rise to the following evolutions of the bottom and center points described by Fig. 6.2.

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

Case B

Simulation results of this configuration (Figs. 6.6 and 6.7) indicate that, differently from case A, the sphere has to be advantageously stiff, so that actuation produces no local strain on it. In fact, the jumping capability in this case depends on the possibility to lift the dummy mass in the first active phase, by electrically compressing the actuator and avoiding the deformation of the sphere. This actually permits to accumulate elastic energy into the actuator and, at the same time, to raise the center of gravity of the system. This is confirmed by Figs. 6.6 and 6.7, in which it is interesting to note that, during the 0.2-second-long active contraction phase, the dummy mass is lifted. Then, following the de-activation of the electrical stimulus, the passive elongation of the actuator (due to the strain energy) will tend to pull the sphere upward and, at the same time, to push more or less strongly (depending on the mass ratio) the dummy mass downward.

Scale-invariance of results

Owing to the theoretical scale-invariance of the performances of dielectric elastomer actuators and to the linearity of the constitutive relations assumed in the simulations, these results can be reasonably assumed as linearly scalable for a system having dimensions one order of magnitude higher.

However, an eventual bigger system would imply an increased mass of the sphere. In case B, this will require, in order to preserve an advantageous mass ratio, a higher dummy mass and a larger actuator (or a parallel of devices) capable to sustain and lift the mass.

Environmental constraints

Concerning the sensitivity of candidate materials (silicone rubber) to the space conditions of radiation and temperature, no literature is currently available.

However, with respect to temperature conditions, a general issue can be taken into consideration. It is opportune to stress that the glass transition of silicone rubbers prevents their use at low temperatures (-55 °C on the surface of Mars). One possible means to overcome this limitation would consist of a heating of the actuator, in order to increase its working temperature.

So far, no experimental measurements have been performed concerning the sensitivity of the materials to radiation.

8. Conclusions

Two configurations (case A and case B) have been proposed for the implementation of a "Mars jumping rover", based on an elastic sphere having a diameter of 2 m, actuated by an internal dielectric elastomer actuator capable of linear electromechanical contractions.

Numerical simulations performed on both the configurations suggest, within the limits of the assumptions and the simplified analysis performed, the superiority of the configuration of case B. By assuming for the actuator active contraction strains of -10%, reasonably achievable with the application of electric fields of the order of 25-30 V/μm, simulation results indicate that this configuration enables displacements of the bottom point of the sphere of 15.2 cm, corresponding to the 7.6% of the diameter of the sphere.

However, the simplified nature of the performed analysis suggests, in reason of these interesting results, to consider a jumping eight of the order of 10 cm (5% of the diameter of the sphere) as a first-approximation over-estimate of the effective jumping capabilities of such a kind of system.