Architecture for the semi-automatic fabrication and assembly of thin-film based dielectric elastomer actuators.

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ABSTRACT

One problem related to the actuation principle of macroscopic dielectric elastomer actuators is the high voltage required, typically in the Kilovolt range, that imposes particular care in the insulation of the whole actuator from the surrounding environment. This high actuation voltage, however, can be drastically reduced if a thin film of dielectric elastomer is used. Despite this, the manufacture of a macroscopic stack-like actuator, starting from thin films of dielectric elastomer can present many manufacture difficulties, like the handling and the assembly of the films, the power distribution to hundreds or thousands of layers, the presence of defects in one single layer that can cause the complete failure of the whole actuator. In this paper, a fast, semi-automatic process is proposed for the manufacture of modular units of dielectric elastomer, each of them consisting of many layers of rolled thin dielectric film. All the manufactured units are independent and take their power from a lateral, compliant supply rail that contacts the sides the electroded layers. This design is very suitable for industrial production: each module can be independently tested and then assembled in a complete macroscopic actuator composed by an unlimited number of these modules. The simple assembly methodology and the semi-automatic manufacture process described in this paper allows the fabrication of multilayer stacked devices, that can be used both as contractile or expanding actuators.

Keywords: Multilayer dielectric elastomer actuators, thin-films, semi-automatic fabrication procedure

1. INTRODUCTION

Electroactive Polymers (EAPs) are polymers able to respond to electrical stimulations, modifying their shape when an external voltage is applied to them[1][2]. For this reason, EAPs are also often called “artificial muscles” because, even if they don’t share the same operative principle of biological muscles, their functional response is similar, and they have characteristics of generated stress and strain approaching the capabilities of the mammalian muscles. These peculiar characteristics of EAPs make them extremely attractive for the study of novel actuation mechanisms, and it is expected that their continuous improvement in terms of performance and reliability will open new perspectives to fields like prosthetics, robotics, telepresence, rehabilitation etc.

Dielectric Elastomer Actuators (DEA)[3][4] represents one class of electroactive polymers that have already demonstrated good performances and offer great potentials for mechatronic and robotic applications, especially in the field of biomimetic mechanisms and humanoid robotics. DEAs are in fact superior in terms of lightness and energy efficiency to traditional electromagnetic actuators and own an intrinsic softness that makes their use advantageous when a safe, compliant interaction with the surrounding environment is required. Compared to many other EAPs, moreover,

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dielectric elastomers actuators are also able to produce high strains and forces, and respond to externally applied electrical stimuli with fast operation cycles.

In its basic configuration, a dielectric elastomer actuator is a “rubber capacitor”, consisting of an elastomeric film (the dielectric), with the two faces coated with compliant electrodes. When a high voltage difference is applied to the two electrodes, positive charges appear on electrode and negative charges on the other, generating an electrostatic attractive pressure know as Maxwell stress (Fig. 1). This stress is equal to the permittivity of the elastomeric dielectric multiplied by the square of the applied electric field. All dielectric materials experience the effect of Maxwell stress, but if a an elastomer with low Young modulus and high breakdown strength is used as dielectric medium, the electrostatic pressure will force the electrodes to come closer, squeezing the dielectric elastomer layer. Since the dielectric medium is an elastic but incompressible material, the elastomer will reduce its thickness and, at the same time, will expand its area on the plane perpendicular to the electrostatic Maxwell pressure.

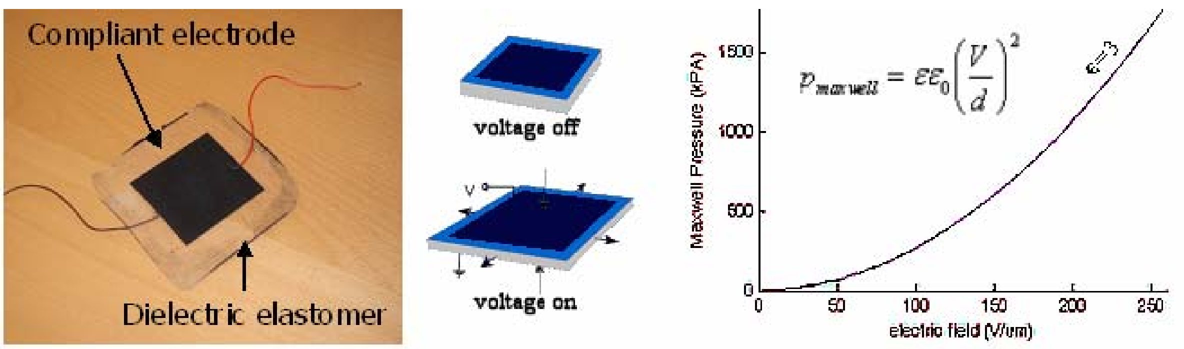

Fig. 1. Operation principle for a single-layered dielectric elastomer actuator and theoretical evaluation of Maxwell pressure in function of the applied electric field.

This very basic configuration, composed by a single layer of dielectric elastomer is typically used in laboratory tests to evaluate the performances of the materials used as dielectric and compliant electrodes[5][6][7]. However, practical mechatronic applications that have the demand of large amounts of generated strain and force require different and more complex configurations than the one just described. In order to produce effective mechanical work, a dielectric elastomer actuator can be exploited in two different ways: as a contractile unit, if the attractive force between the electrodes is directly used to produce work, or as an expanding unit if the areal expansion of the electrode is exploited. All possible configurations, in which a dielectric elastomer is used as an actuator, employ one of these two operation principles.

Typical contractile actuator can be schematized as a stack of many identical layers connected electrically in parallel (Fig. 2a). When the voltage is applied, the stack is compressed by the electrostatic attraction generated by each layer, resulting in an overall contraction. For a multilayer stack, the contractile strain displacement depends on the height of the stack, while the generated force is proportional to active axial cross-section covered by the compliant electrodes.

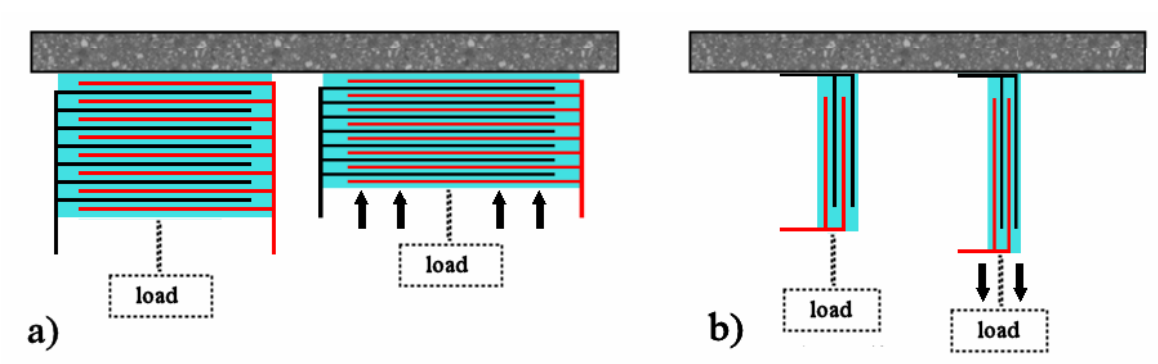

Fig. 2. Operation principle for multilayer DEAs used to produce contractile motion (a) and expanding motion (b).

An implementation of this basic operating principle has been practically realized in many different ways, bringing to different fabrication methodologies and, of course, to actuators with different characteristics. Helical structures[8], folded geometries[9] and spinned[10] or assembled multilayer actuators[11] are some effective possibilities to obtain a linear contractile motion.

Dielectric elastomer can also be used as an expanding device, if the areal expansion of the electrode is used to produce mechanical work (Fig. 2b). In this case, the displacement generated by the actuator depends on the areal size of the compliant electrodes, while the generated force depends on the thickness (cross-sectional area) of the actuator. So, while for the contractile configuration a multilayer stack is required to achieve greater displacement along the main axis, for the expanding configuration, many dielectric elastomer sheets need to be stacked in order to achieve a higher cross-sectional area and greater actuation force. It must be noticed that, due to softness of the elastomeric material, the expansion movement produced by this configuration cannot be used directly to push a load. For this reason, expanding actuators are generally used together to some kind of mechanism (typically a spring or an external load) that keeps them in a stretched state and work in the opposite way respect to the contractile actuators. When no voltage is applied, the actuator remains in the contracted position. On the contrary, when an external voltage is applied, the elastomer expands and a new equilibrium position with the external spring is found, allowing the movement of the load. The prestrain mechanism adopted for expanding DEAs is also useful because the alignment of the polymer chains result in an increase of the breakdown strength, allowing the application of a greater electric field[4][12]. As for the contractile configuration, also this expanding configuration can be implemented in different ways and with different geometries, like diamond actuators[13], cone actuators[14], spring rolled actuators[15][16] and many others.

2. FABRICATION OF THIN-FILM BASED ACTUATORS

2.1 Preliminary considerations

One problem related to the actuation principle of macroscopic dielectric elastomer actuators is the high voltage required, typically in the Kilovolt range, that imposes particular care in the insulation of the whole actuator from the surrounding environment. This high actuation voltage, however, could be drastically reduced if a thin film of dielectric elastomer is used. For example, let’s consider an electric field of 15V/um, a typical actuation value for non prestrained actuators. This electric field will results in applied voltage of 9000V for 0.6 mm thick dielectric layer and 750V for a 50um thick dielectric film. This trivial calculation shows how much is preferable to have an actuator made of thin dielectric layers.

Unfortunately, the fabrication of a macroscopic stack-like actuator, starting from thin-films of dielectric elastomer can present many manufacture difficulties. The first difficulty is the handling and the assembly of the films. On the contrary of many strong polymers that are commonly used as thin films in the electronic and textile industry (like Kevlar, Polyimides etc.), the elastomer commonly used for the fabrication of DEAs (i.e. silicones, acrylic rubber etc.) are quite fragile and can be easily broken during handling, especially films with thickness smaller than 100um. This fact makes difficult the development of a fabrication process in which complex mechanical manipulations of the thin film are performed, like in the case of folded actuators. Other techniques, like the controlled deposition and spinning layer by layer of curable prepolymers, can present different difficulties. First of all, the presence of a small fabrication defect in one layer can cause cumulative errors that can compromise the deposition of all following layers, leading to the failure of the whole actuator. Moreover, spinning processes are effective only for a limited number of fabricated layers since, as the stack grows in size, the uniformity of the fabricated layer becomes difficult to control. In particular the fabrication of uniform stacks of several cm of length, starting from deposited layers of few microns can be really challenging and requires extremely accurate machines. Finally, the discontinuous nature of an actuator composed by hundreds of layers of deposited dielectric can make the electrodes complex to contact.

All the previously exposed considerations are both valid for multilayer stacks used to produce contractile motion (the stacking is used to increase the displacement of the actuator) and expanding motion (the stacking is used to increase the force of the actuator). To try to overcome to these manufacture difficulties, a different configuration was investigated, that allows the semi-automatic fabrication of a multilayer stack actuator.

2.2 Proposed fabrication technique for thin-film based DEAs.

Due to mechanical fragility of a thin elastomeric film, a procedure that avoids articulated mechanical manipulations and potentially harmful stress is needed. One first, simple idea to produce rolled multilayer stacks comes from the fabrication process of rolled-type polyester capacitors. In fact, if an electroded dielectric film is wound on a flat removable core, a device functionally equivalent to a multilayer stack can be obtained (Fig. 3).

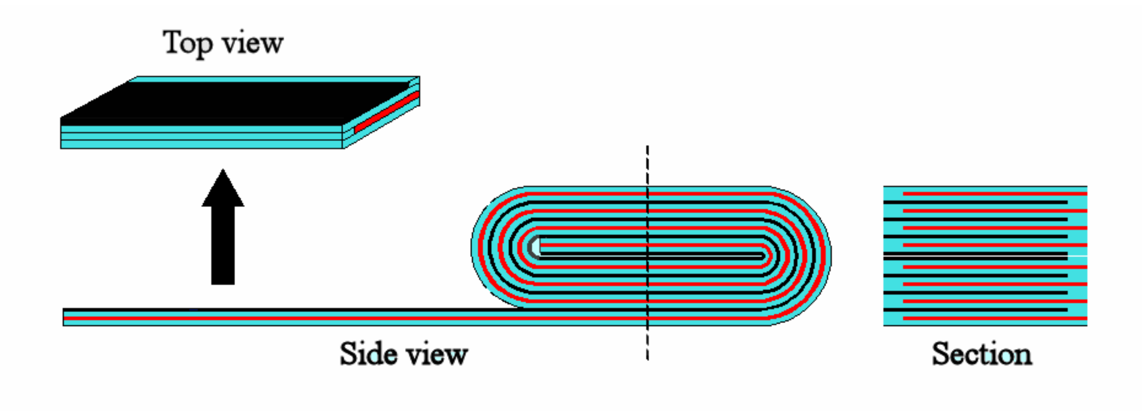

Fig. 3. A multilayer stack configuration obtained rolling the electroded dielectric film on a flat removable core.

Despite to its simplicity, if this geometry is used to fabricate a multilayer stack DEA, the actuator will suffer of a serious mechanical problem. As the size of the roll grows up, the amount of material that does not produce useful mechanical work increases. The electroded sides of the stack, in fact, will generate a compressive force that opposes to the overall contraction motion along the main axis. This configuration sets thus a practical limit on the maximum number of layers that can be present in the rolled actuator.

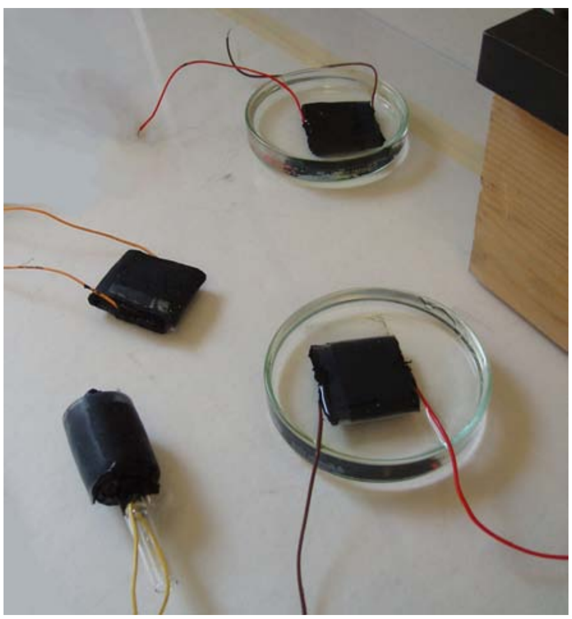

Fig. 4. Prototypal DEAs fabricated in different shapes and sizes.

This rolled geometry can be however optimized in order to obtain multilayer stacks that do not suffer of the previously described problem. In particular, if the electrodes are fabricated during the winding process, it will be possible to obtain geometries in which the areas that do not produce useful mechanical work are not-electroded and can be mechanically removed after the winding phase. The proposed methodology, implemented with an ad-hoc built winding machine, is described in the following section.

3. SEMI-AUTOMATIC FABRICATION SETUP

The fabrication process of the actuator is divided into two different steps. The first step is the fabrication of the multilayer stack using the semi-automatic machine described in section 3.1. The second step is the fabrication of the lateral contacts and the packaging of the stack into the final actuator.

3.1 Fabrication of the multilayer stack

For the fabrication of the multilayer stack, a semiautomatic procedure was developed using a custom built winding machine. The fabrication procedure is showed schematically in Fig. 5. A roll of raw material (dielectric elastomer) is loaded into the machine. A motorized unit, provided with an optical encoder, is then used to wind-up the material keeping track of the angular position of the rotor. In pre-programmed angular positions the motor is stopped, an electro valve is opened and a conductive elastomer pre-polymer is airbrushed on the roll through a mask. Depending on the current layer of the roll, different masks are used, in order to produce shifted electrodes. According to Fig. 5, a mask A is used to produce bottom-aligned electrodes on all even layers of the roll, mask B is used to produce top-aligned electrodes on all odd layers of the roll. After the spray deposition of the electrodes, the motor is moved to next position and the process is repeated until a roll with desired radius is fabricated. It must be noticed that the radius of the roll will be also the height of final multilayer stack. Depending on the required geometry of the actuator, the winding motor can be programmed to be started and stopped in as many angular positions as desired, and many multilayer stacks can be built during the same process.

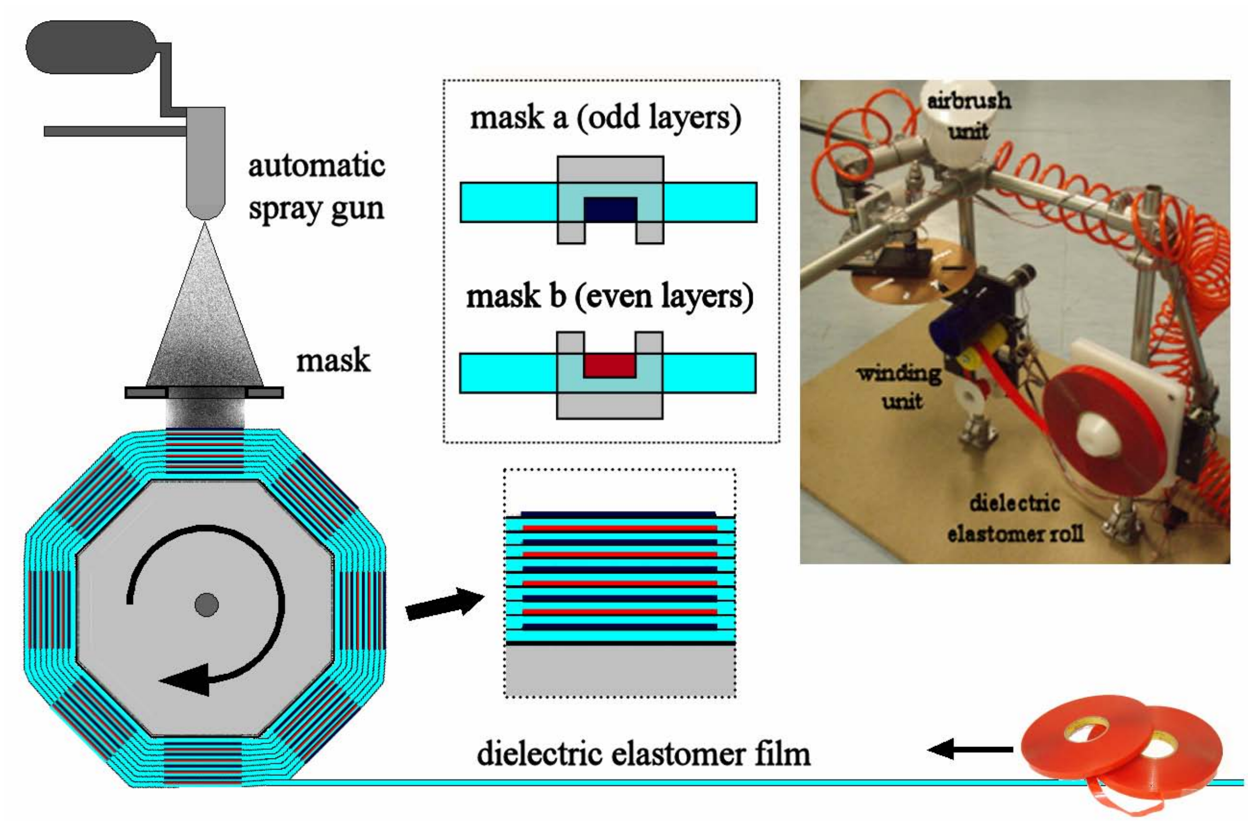

Fig. 5. Semiautomatic fabrication process of multilayer stack actuators.

3.2 Packaging of the actuator

After having reached the desired number of layers, the manufactured roll is kept to rest until the sprayed conductive electrodes are fully cured. This time varies depending on the materials used as dielectric elastomer substrate and as compliant electrodes. At least few hours of rest are advisable in order to achieve a full cure of the polymer and a good mechanical bonding between the layers. The roll manufactured in the first step of this process is then cut radially in order to obtain the number of multilayer stack actuators decided during winding phase. In fact, as previously shown in Fig 6, multiple stacks can be cut from the roll. Each stack (Fig 6a) is then processed to remove a small amount of side material in order to be sure that the electrodes are properly exposed (Fig 6b). Finally the two lateral faces of the multilayer stack are airbrushed with the same conductive elastomer used for the electrodes fabrication, in order to connect all the electrodes to the positive and negative power supply cables (Fig 6c). The actuator is also finally packaged and externally insulated.

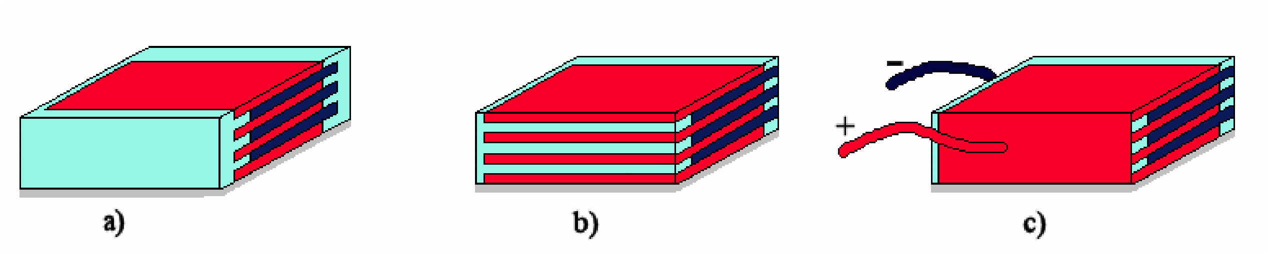

Fig. 6. Connection of the electrode layers. The inside structure of the stack is here exposed only for picture clarity.

4. ACTUATOR GEOMETRIES

The described procedure can be used to fabricate dielectric elastomer actuators of with different geometries, both contractile and expanding. Depending of shape and the size of the masks, in fact, different electrodes patterns can be airbrushed on the dielectric film resulting in final actuators with different motion behaviors.

4.1 Contractile actuators

For the fabrication of actuator prototypes, masks openings of 2x2cm were used. Compliant electrodes were fabricated airbrushing a mixture of a two-component commercial silicone/polyurethane rubbers and carbon black previously dispersed in toluene. The choice of the electrode formulation was studied in function of the dielectric substrate, in order to improve the adhesion between the electrodes and the dielectric elastomer. In particular, silicone electrodes were used on silicone dielectric elastomer, while polyurethane was preferred for acrylic dielectric elastomer. 3M's VHB tape is an acrylic elastomer commonly used for the fabrication of DEAs because its good dielectric properties [4]. For the fabrication of acrylic elastomer actuators, commercial rolls of VHB tape with different thickness (starting from 0.5mm for VHB4905 down to 50um for VHB9460) were used. Of course, the fabrication time of the multilayer DEA depends on the chosen thickness of the film. For example, an actuator 1cm high will require 20 layers of VHB 4905 and about 200 layers of VHB9460. In order to save fabrication time and raw material, the simultaneous manufacture of many multilayer stacks can be programmed on the machine, by scheduling the fabrication of each actuator at a different angular position of the roll, as depicted in Fig 7. It must be noticed that these stacks, can be also further assembled together in order to obtain actuators of different sizes and geometries Fig 8. In this way, the handling and the assembly of these macroscopic stacks will be much simpler. This modular assembly will also allow a functionality check of each module before the complete assembly. If the one module will result defective, it will be simply discarded, instead of compromising the functionality of the whole assembled actuator.

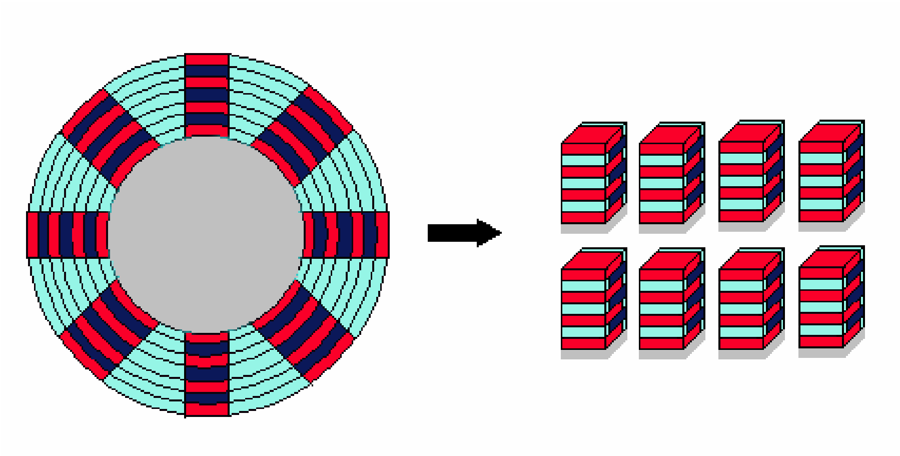

Fig. 7. Schematic fabrication of eight contractile actuators (multilayer stacks) starting from the previously fabricated roll.

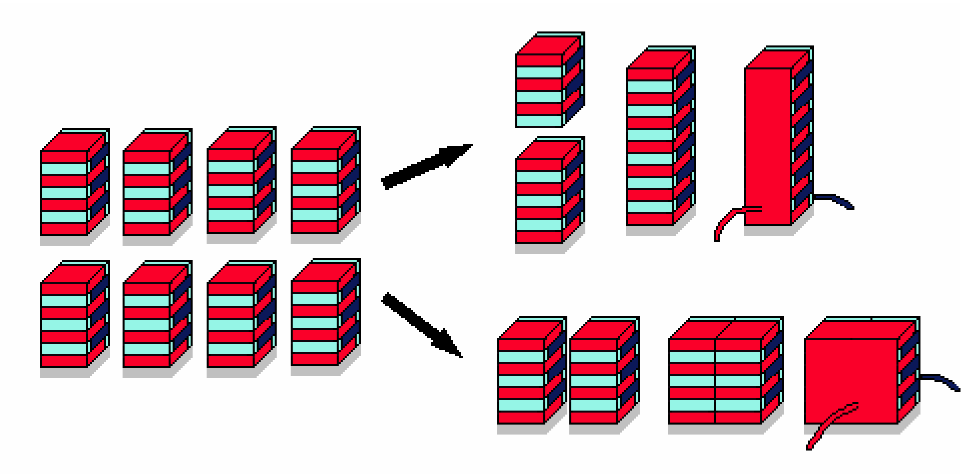

Fig. 8. Assembly of many independent contractile units in bigger actuators packaged in series or in parallel.

4.2 Expanding actuator

An expanding actuator can be obtained simply varying the deposition pattern of the compliant electrodes on the dielectric film. For the fabrication of large conductive areas, the compliant electrodes can be deposited during the rotation of the winding motor. In this way, a larger area of dielectric elastomer will be covered by the compliant electrodes (Fig 9).

One peculiar characteristic of dielectric elastomer films is the enormous increment of their breakdown strength when a prestrain is applied. Using a prestrained film, higher electric fields can be applied to the actuator, resulting in a increase of the generated Maxwell pressure and the overall displacement of the device[4]. Multilayer stacks fabricated with the proposed technique can be obviously prestrained, using an external frame or support that keeps the material stretched along one or the two planar directions. Compliant rubber electrodes, made of carbon-black filled polyurethane elastomer have demonstrated to keep sufficient conductivity (few hundred of kilo ohms) even when the dielectric elastomer substrate is biaxially stretched. For this reason, the fabricated multilayer stacks can be stretched and assembled on the desired frame after the process of deposition of the compliant electrodes. Finally, it must be noticed that the generated force for this kind of actuator is proportional to its cross-sectional area. A multilayer geometry composed by hundred of stacked thin elastomeric layers will reduce the actuation voltage maintaining an actuation force comparable to the one of a single layered actuator with same overall thickness.

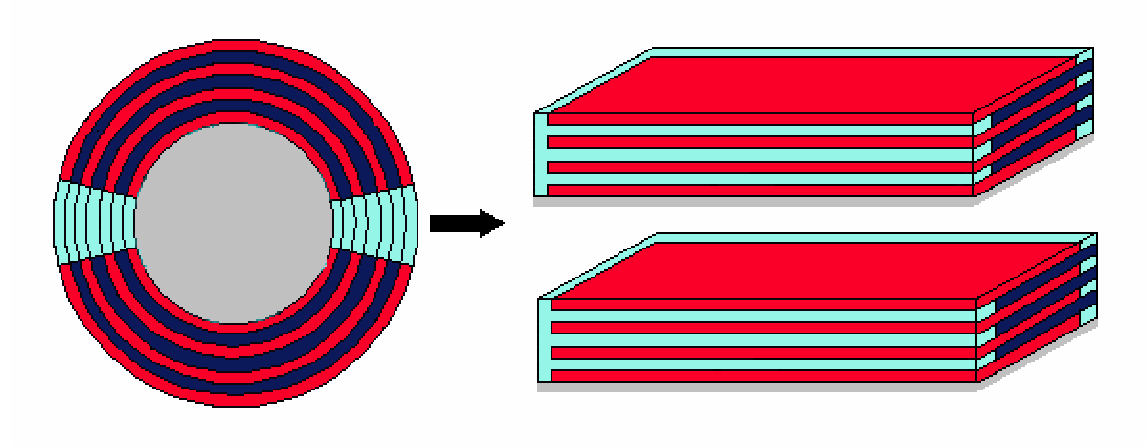

Fig. 9. Schematic fabrication of two expanding actuators (multilayer stacks) starting from the previously fabricated roll.

5. CURRENT EXPERIMENTAL WORK

Preliminary experiments are actually in progress to evaluate the performances of the fabricated multilayer actuators. An experimental setup composed by an hi-resolution camera (Hamamatsu C4742) connected to a Labview program that generates the appropriate electrical stimuli and performs optical measurement is used to evaluate the strain of the actuator in function of the applied voltage (Fig 10) .

Fig. 10. Optical setup for the measurement of the electromechanical properties of the prototype actuator.

Preliminary tests, conducted on prestrained prototype actuators made of VHB tape, showed large differences in the produced lateral strain, varying from 5% to 12%, depending on the actuating configuration (contraction/expansion) and the dielectric material used (VHB4905 / VHB9460). Experiments showed also a considerable viscous effect depending on the viscoelastic properties of both the acrylate dielectric and the polymeric matrix used to fabricate the compliant electrodes (Fig 11). For this reason, the topography, the quality and the interaction between the fabricated electrodes and the dielectric substrate were examined by an Ultra High Resolution Field Emission Scanning Electron Microscope and Focused Ion Beam (model CrossBeam® 1540XB by Zeiss) (Fig12)

Accurate measurements are actually in progress in order to evaluate the performances of multilayer stacks actuators, in order to understand which parameters are crucial to optimize the fabrication process and obtain the maximum actuation performances.

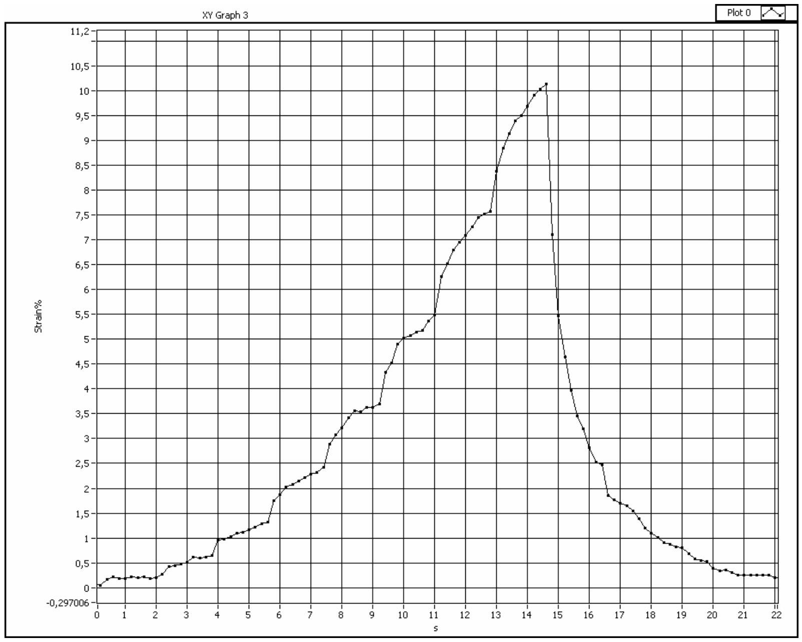

Fig. 11. Viscous behavior of an acrylic (VHB) DEA. Lateral strain is here presented vs time, in response of voltage steps of increasing magnitude.

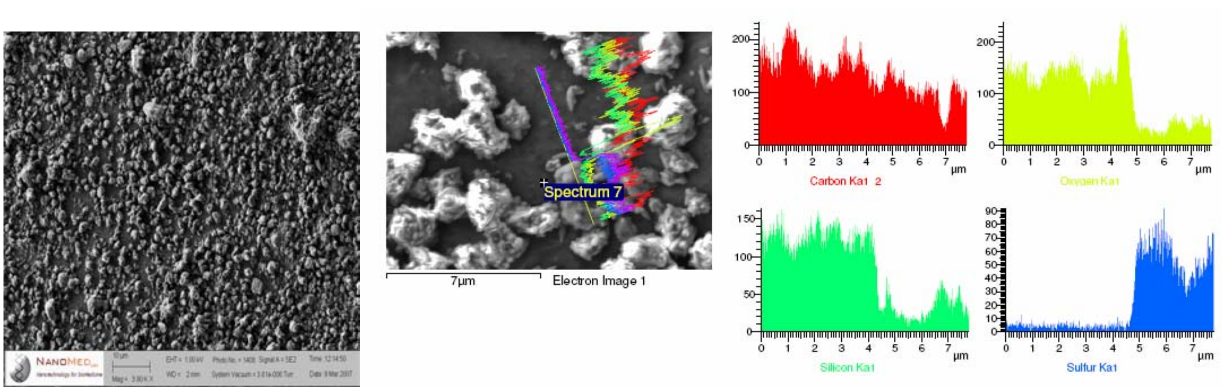

Fig. 12. SEM and X-Ray Microanalysis of the airbrushed compliant electrodes.

6. CONCLUSIONS

In this paper a semiautomatic process for the fabrication of actuators composed by multilayer stacks of dielectric elastomer films is presented. The proposed technique can be applied to fabricate both contractile and expanding multilayer devices. Multilayer contractile actuators benefit from the described technique for the simplicity of the fabrication process that automatically deposits the compliant electrodes and bonds together the layers of the stack. Similarly, expanding actuators constituted by thin films can be arranged in a multilayer configuration to have a higher cross sectional area (thickness) and to develop more force. Finally, the employment of thin dielectric elastomeric films for the fabrication of macroscopic multilayer DEAs allows a significant reduction of the actuating voltage. Experimental measurements are currently in progress in order to evaluate the electromechanical performances of the fabricated multilayer DEAs. It must be also observed that, the more the size of the dielectric layer is scaled down, the more it becomes comparable with the thickness of the deposited electrode. For this reason, further investigation will be carried out to better understand how electrodes of different materials, geometries and thickness interact with the dielectric layers and affect the macroscopic performances of the actuator.

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