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# Field Induced Deformation of Active Structures Based on Dielectric Elastomers

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## ABSTRACT

In the last decade the interest for "active material systems", which respond to external stimuli by changing their shape or size, has increased. Among the different classes of active materials the broad family of "dielectric elastomer" is currently drawing a significant scientific interest, since they are capable of responding to electrical stimuli, with significant changes of size and shape. The operating principle of dielectric elastomer (DE) is based on Coulomb (Maxwell) forces generated by electric (static) fields which results in squeezing of the dielectric film and therefore in large deformation of the entire composed structure. Since the dielectric elastomer film squeezes in thickness direction and expands in planar direction at applied electrostatic field two different basic actuation modes of the DE structure can be achieved as they are the expanding or contracting deformation. In this paper the "expanding" actuator based on the membrane design and the "contractive" active structure composed of many layers in stack design are reviewed with special focus on both actuation modes under external loads. Additionally some challenging technological aspects are discussed concerning manufacturing process and design parameters. Based on today made experiences and ongoing research activities the potentials of future active structures can be estimated due to the expected electromechanical properties of new materials.

**Keywords:** Electro active polymer (EAP), dielectric elastomer (DE), membrane actuator, contractive stack actuator, shell-like actuator

## 1. INTRODUCTION

In the last decade, the interest for "smart materials", which respond to external stimuli by changing their shape or size, has essentially increased. Among the active materials, in particular soft dielectric elastomer (DE) as muscle-like actuators, a subgroup of the electroactive polymers (EAP), have attracted much interest in recent years due to their outstanding active deformation potential [1–4]. This broad family of "smart polymer materials" is currently drawing a significant scientific interest, since they are capable of responding to electrical stimuli, with significant changes of size and/or shape. In fact, this class of materials is currently the most performing among all of the available EAP representatives, as shown by the state of the art reported in Section 1.2. In particular, DE shows very attractive overall electromechanical transduction properties, along with advantageous mechanical features in terms of extreme lightness and very large compliance. Accordingly, DE actuators offer today the great potential of being capable of enabling really innovative actuation systems. The specific properties of DE materials and devices make them particularly suitable for developing light and flexible systems. These types of materials and devices may really open new paradigms in the field of adaptive structures, where at present no conventional actuation technology (typically too heavy, stiff and noisy) is capable of offering comparable prerogatives.

The working principle of the dielectric elastomer actuator is similar to the compliant capacitor. It consists of a dielectric elastomer film (e.g. silicone or acrylic elastomer) sandwiched between two compliant electrodes. In this arrangement, the polymer acts as a dielectric in a compliant capacitor. When an electrical voltage is applied between the electrodes, an electrostatic field occurs and electrostatic stresses ($T_{11}$=$T_{22}$ in plane components, $T_{33}$ out of plane component of the Maxwell stress tensor) acting on the elastomer is produced from the charges on the electrodes.

$$T_{11} = T_{22} = -T_{33} = -\frac{1}{2}\varepsilon_0\varepsilon_r\left(\frac{U}{d}\right)^2 \tag{1}$$

As a result, the incompressible polymer material squeeze uniformly and the polymer film is enlarged elastically in the plane, as sketched in Figure 1.

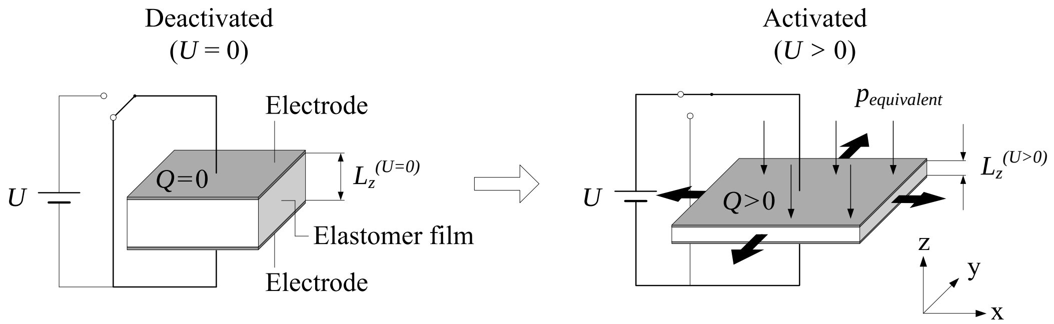


**Figure 1.** Structure and principle of operation of soft dielectric EAP.

As soon as the voltage is switched off and the electrodes are short-circuited the capacitor contracts back to its original size and shape. Using the incompressibility of the elastomer

$$(1+s_x)\cdot(1+s_y)\cdot(1+s_z) = 1, \tag{2}$$

where $s_i$ is the strain in i-direction, the effective pressure $p_{el}$ can be derived that has to be applied in z (thickness)-direction to achieve the same thickness strain $s_z$ as induced by the Maxwell stress. For this derivation the contribution of the 3 direct stress components $\sigma_{xx}$, $\sigma_{yy}$ and $\sigma_{zz}$ has to be distinguished. Assuming that $\sigma_{xx}$ and $\sigma_{yy}$ are zero the thickness strain $s_z$ is described by using the strain modulus Y:

$$s_{z,1} = \frac{\sigma_{zz}}{Y} \tag{3}$$

Expecting that the resulting strain in y- and thickness direction z are equal, $s_{z,2}$ can be written by combining eq.2 and 3:

$$s_{z,2} = \frac{1}{\sqrt{1+\frac{\sigma_{xx}}{Y}}} - 1 \tag{4}$$

If $\frac{\sigma_{xx}}{Y}$ <<1 and using the Taylor series the equation can be simplified to

$$s_{z,2} \approx \frac{1}{1+\frac{\sigma_{xx}}{2Y}} - 1 \approx -\frac{\sigma_{xx}}{2Y} \tag{5}$$

The same is true for the influence of the lateral Maxwell stress $\sigma_{yy}$ acting in y-direction resulting in $s_{z,3}$:

$$s_{z,3} \approx \frac{1}{1+\frac{\sigma_{yy}}{2Y}} - 1 \approx -\frac{\sigma_{yy}}{2Y} \tag{6}$$

The pressure $p_z$ can be calculated by adding all equivalent pressures $p_{z,i} = s_{z,i}$ Y acting normal to the surface:

$$p_z = \sigma_{zz} + Y \cdot \left( \frac{1}{\sqrt{1+\frac{\sigma_{xx}}{Y}}} + \frac{1}{\sqrt{1+\frac{\sigma_{yy}}{Y}}} - 2 \right) \approx \sigma_{zz} - \frac{\sigma_{xx}}{2} - \frac{\sigma_{yy}}{2} = \varepsilon \cdot E_z^2 \tag{7}$$

This equation can be reduced to a simple expression for the so called "equivalent electrostatic pressure" $p_{eq}$ acting in the direction of the E-field, as proposed by Pelrine [5]:

$$P_{eq} = \varepsilon_0 \cdot \varepsilon_r \cdot \left( \frac{U}{d} \right)^2 \tag{8}$$

Thereby $\varepsilon_0$ is the free-space dielectric permittivity ($\varepsilon_0$=8.85×10-12 F/m), $\varepsilon_r$ is the relative dielectric constant of the material, U is the applied voltage and d is the film thickness representing the applied electric field E. By arranging several DE film layers in parallel, the resulting force can be multiplied. Although the passive stiffness of the created actuator is increased, when the actuators are combined in series, the active displacement becomes larger.

## 1-1. Actuator performance

Silicone and acrylic based polymers are most widely used as dielectric elastomers in actuator configurations, due to their excellent elastic and electric properties. Beside the mechanical, electrical and electro-mechanical characterization of the materials, the fabrication and operation of devices is intensively studied and the influence of parameters like different electrode materials, pre-strains or thicknesses of the elastomeric film on the overall performance of the actuators are explored. The acrylic based elastomer VHB 4910 (manufactured by 3M) is a commercially available polymer that exhibits large electro-mechanical strains (up to 210%), producing high pressures (up to 8 MPa) and extraordinarily high specific elastic energy densities (3.4 J/g). It is nowadays the most used material to produce muscle-like actuators. On the other hand silicone based dielectric elastomers, as a further material category, reveal fast responses, rather small dissipative losses and high stability when exposed to extreme environmental conditions (temperature, humidity, etc.). Additionally, silicones can easily be tailored to the specific application when fabricated. However, the strain levels of actuators with silicones (strains of up to 64 %) are smaller compared to acrylic dielectrics. Furthermore lower actuation power density of the silicone film has to be considered due to lower specific breakdown strength of silicone (~30V/µm) in comparison to acrylic film (~100V/µm) at given dielectric constant. Since the handling of silicones is rather simple they are preferred for the preparation of thin films. In terms of the electrodes for soft dielectric EAP actuators, the need for mechanical compliance is usually reached by the application of electrically conductive particles (e.g. metal, carbon black, graphite particles or carbon nano-tubes), which are usually applied by brushing or spray coating. Further methods as sputtering or plasma treatment technologies as well as metal ion implantation have been applied and tested to reach better performances of the actuators and to obtain a smart and soft material system.

## 1-2. Actuator design

So far, a variety of different types of dielectric elastomer (DE) actuators demonstrated the versatile capabilities of this actuator technology (e.g. [6, 7]) and represents the present state-of-the-art regarding actuator types, as they are the extender (planar), unimorph-, bi-morph-, stack-, folded-, helical-, spring roll-, push-pull-, bow-tie-, diamond-, diaphragm-, spider- ,inchworm segment- and universal muscle actuator.

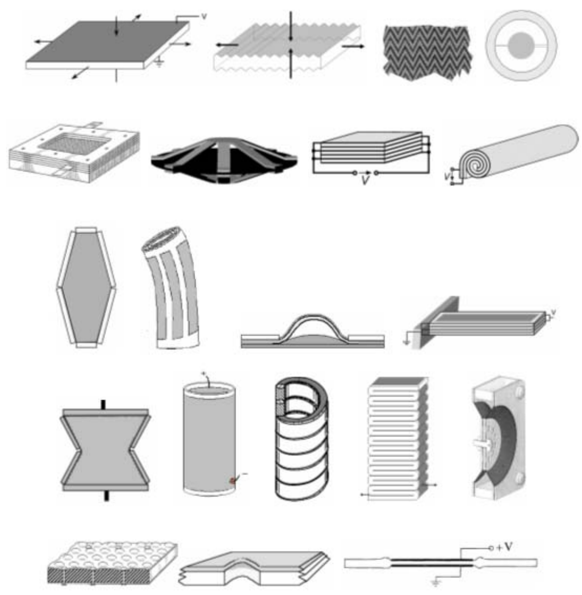

**Figure 2.** Actuating configurations for dielectric elastomer actuators.

Figure 2 shows schematic drawings of the most significant fundamental actuating configurations currently available for dielectric elastomer actuators [7]. Examples of such applications include mobile mini and micro robots, micro air vehicles, disk drives, flat panel loudspeakers, electro-acoustic transducers and many other adaptive structures. However a commercial application is not jet on the market. Main obstacles for broad applications are the high actuation voltages (kV range) and the unsatisfying long term behaviour of DE actuators.

## 1-3. Actuation mode

In general the actuation of the dielectric elastomer film can be used in different ways. Based on the principle of operation of soft DE, mainly two directions to perform work against external loads are possible:

- Work in planar directions (in-plane expanding actuator): Under electrical activation of a DE membrane the film expands in planar directions and can thus work against external load acting in both planar directions.
- Work in thickness direction (out-of-plane contractile actuator): Under electrical activation the electrodes squeeze the DE film in thickness direction. Thus, the actuator can work against external tensile loads acting in thickness direction.

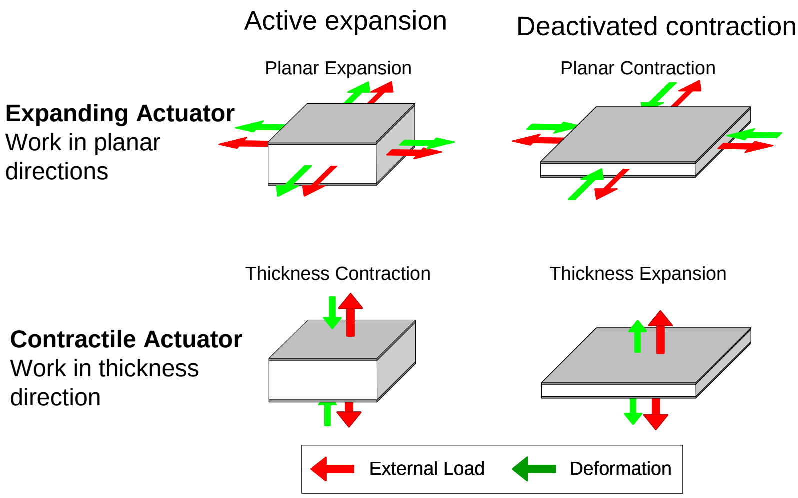


**Figure 3.** Actuation modes: In-plane expanding – out-of plane contractive actuation

The different actuation modes of the actuator represent the most significant issue in terms of actuation property (expansion – contraction when activated), performance and lifetime. The two actuation modes results in very different actuator designs and properties in respect of one-dimensional actuation deformation:

- Planar expanding actuation of the rolled actuator type
- Contraction by film thickness change of the stacked actuator design.

Up to now most scientific research work has been focused on the planar actuation mode due to the fact that the acrylic material with intrinsic very high actuation performance as dielectric is easily available in thin film form. In this constellation the film has to be pre-strained in order to prevent any mechanical instability (buckling) when voltage is applied. Additionally many experiments have displayed an essential increase of the electric breakdown strength of the film when it is pre-strained [8-12] which results in a high field strength (>100V/µm). To maintain the DE film in this biaxial pre-strained state a support structure is needed. For enabling the required displacements with soft dielectric EAP, this support structure must offer the corresponding mechanical degrees of freedom

(DOF). Obviously, with pre-strained DE actuators the design of the support structure is one of the key issues and leads to many design constraints.

The main drawbacks are therefore the necessity of mechanical pre-straining of the film which has to be maintained during actuation and the fact, that expansion occurs when activated. Beside of the actuation mode insufficient reliability and unpredictable long term behaviour are further disadvantages up to date. To overcome these major problems new actuator designs have to be evaluated which produces contraction motion when actuated. For this reason the actuator in pile-up configuration represents the alternative design to produce contraction motion in film thickness direction when voltage is applied. As a result other (new) materials have to be evaluated which have to be applied in the stress-free condition. Silicones and post-processed acrylic film offers newly the option of designing novel actuators at high performance and overall good reliability.

In the following two chapters both actuator working principles are presented with different designs and a few special issues are discussed in details.

## 2. EXPANDING MEMBRANE ACTUATOR

### 2-1. Theoretical Considerations

Recall that many different actuator designs have been carried out for experimental purposes and represent the present state-of-the-art. They all have similar basic electro-mechanical characteristic: The actuator expands in plane when voltage is applied and shrinks back as soon as the applied charges are removed from the electrodes.

In order to obtain maximum electro-mechanical performance (especially for the commercially available acrylic film VHB 4910 from 3M) and for preventing any mechanical instability these dielectric films need to be strongly pre-strained in both planar directions (levels of 400%x400%). In analogy to the muscle-skeletal structure proposed by nature, one configuration where the pre-strained DE films as "muscles" are attached to a flexible support structure seems to be promising for most actuator design. Thereby, the main requirement for the support structures is to maintaining the DE film in its biaxial pre-strained state. The same is true for all foreseen deformation states.

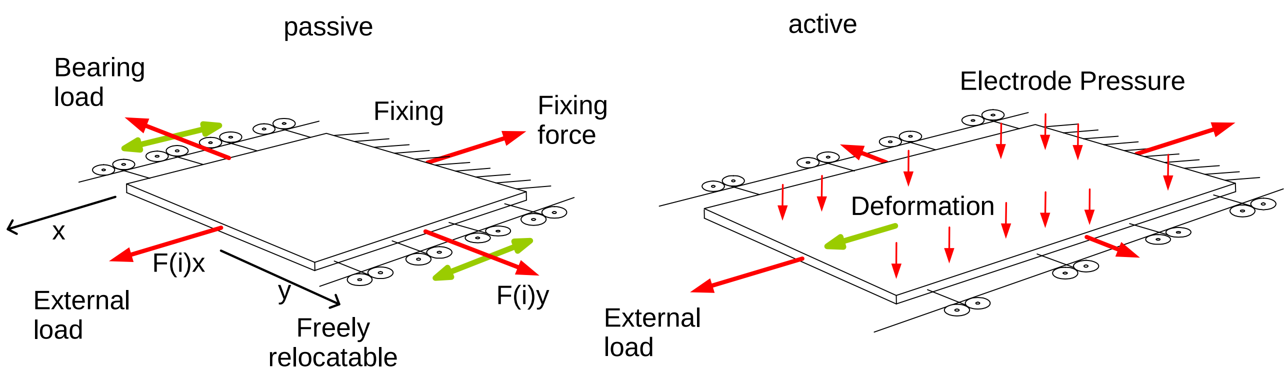


**Figure 4.** Working principle of the pre-straining support structure for operation of soft dielectric EAP.

For most applications a bi-axial deformation behaviour when voltage is applied is not desired. To overcome this problem and to produce unidirectional deformation the most preferred solution for the boundary conditions of a planar DE actuator with one DOF is presented in fig.4 left. The biaxially pre-strained DE film is fixed in the x direction at one end, while at the other end a pre-strain force, F(i)x = const., maintains the pre-strain in the film (isotonic boundary condition). In the y direction, the pre-strain is sustained by discrete clamps, which can be freely relocated in the x direction (isometric boundary condition). In the ideal case the discrete fixing with clamps would be replaced by a continuous bearing, which is perfectly compliant in the x direction, while being capable of taking the tensile forces, F(i)y , in the y direction. Under electrical activation the film is loaded with the equivalent electrode pressure, $p_{el}$, in the thickness direction (fig.4 right). As a result, the film expands in the x direction. At the same time the lateral bearing forces, Fy, are expected to change both due to the transmission of the equivalent electrode pressure in the planar directions as well as the film elongation in the x direction. As soon as the actuator is deactivated, the equivalent electrode pressure is reduced to zero and the film contracts back to the pre-strained initial state.

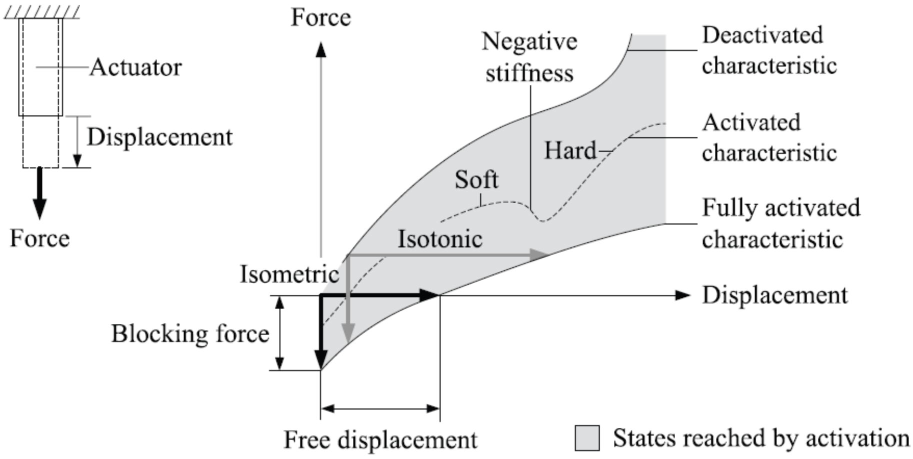


**Figure 5.** Force – displacement characteristic of soft dielectric EAP.

The basic mechanical characteristic of a DE actuator is similar to a non linear adaptive spring. When conventional mechanical structures are loaded with a given set of external forces, a specific equilibrium state of deformation is achieved. The same is true for the elastic DE actuator but its deformation state can be changed by activation. This feature enables the device’s stiffness control since the force vs. displacement behaviour can be electrically influenced. In general the stiffness is defined as the derivation of the external force with respect to the displacement of the corresponding point of application. Accordingly, the stiffness of any active element corresponds to the slope of the tangent at the (deactivated or activated) force vs. displacement characteristic. In fig.5 all the accessible states of an active element with finite passive stiffness are given by the shaded domain between its limiting deactivated and fully activated force vs. displacement characteristics. By specific activation, the actuator can follow different curves within this area and thus simulate, for example, soft or stiff behaviour. As shown, even negative stiffness can be achieved, where an increasing tensile force induces a contraction of the actuator. This effect represents the most important issue to display the capability of producing mechanical work in closed loop mode. The stiffness adjustment potential is basically limited by the capabilities of the actuator technology. The blocking force and the free displacement, as two important characterization parameters, are obtained under different boundary conditions, i.e. isometric and isotonic tests. As a consequence, a DE actuator can never provide the blocking force and the free displacement at the same time.

For conventional types of DE actuators, a variety of approaches have been proposed to maintain the biaxial pre-strain in the DE film, while allowing free elongation in at least one direction. Selected configurations are briefly described as next:

**Planar actuators:**

In general, with planar DE actuators the pre-strain in the x direction as the working direction, is maintained by an external pre-strain force (fig.4). In the y direction, on the other hand, the pre-strained film is clamped with rigid struts.

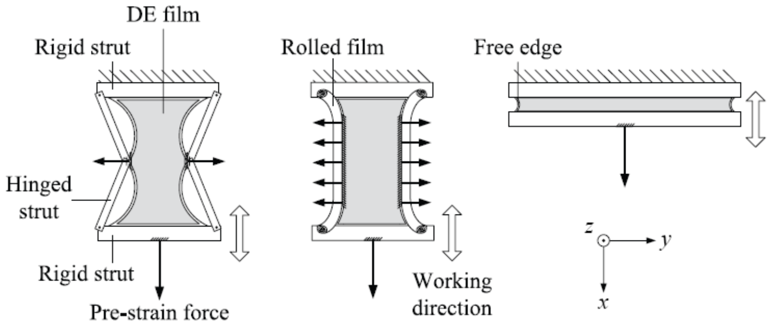


**Figure 6.** Working principle of expanding soft dielectric EAP membrane

In order to preserve the pre-strain of the film in the y direction, the following approaches have been reported:

- Hinged frame support: By the introduction of a hinged frame (fig.6 left) the free edges of the film are braced by rigid, rotatable struts (bow-tie configuration [7]).
- Elastic support [13]: By rolling the dielectric film along its free edges, elastic columns are created, which support the free edges of the film (fig.6 centre).
- Aspect ratio: When the actuator has a wide aspect ratio so that the free edges are short compared to the length of the rigid struts, the contraction of the film in the y direction remains small (wide DE strip actuator [14]). Thus, the biaxially pre-strained state is widely maintained across the DE film without any additional reinforcement of the free edges (fig.6 right). By switching several wide DE strip actuators in series the active displacement of this actuator type can be scaled up [13].

**Rolled actuators:**

Rolled DE actuators consist of a stack of two biaxially pre-strained and coated DE films, which are wrapped around a compressed coil spring core. Under activation, the actuator elongates in its axial direction due to the circumferential constraint. According to the actuator design, one has to distinguish between whether the pre-strained DE film is rolled around a stiff or around a soft coil spring.

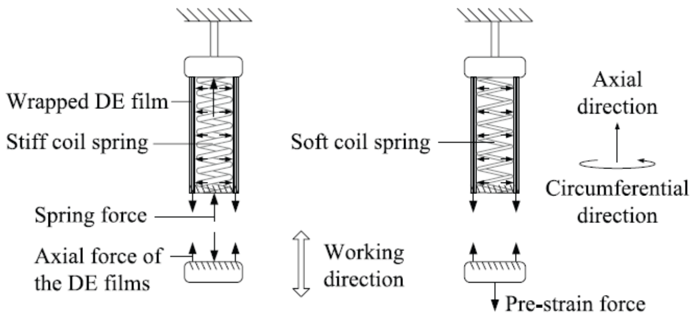


**Figure 7.** Structure of rolled dielectric elastomer actuator with spring core

In both cases the circumferential pre-strain of the film is sustained by the coil spring core (fig.7). However, the pre-straining of the DE film in axial direction differs:

- Stiff coil spring [6, 16]: In the free-standing state the compressed coil spring pre-strains the DE film in the axial direction (fig.7 left).
- Soft coil spring [17]: With this configuration, an external prestrain force (e.g. a weight) is required to reach the desired axial pre-straining of the DE film (fig.7 right).

The rolled DE actuator with a stiff spring has the advantage that it is self-standing, whereas using a soft coil spring an external force is required. Taking into account the decreasing force characteristic of the stiff coil spring under active elongation of the actuator, however, larger active elongations in the axial direction are expected from the second configuration, assuming a constant pre-strain force.

**Inflated actuators:**

The basic idea of this design is to inflate a closed envelope of DE film and thus pre-strain the film with compressed gas. The simplest inflated configuration is a spherical balloon actuator, which consists of an inflated bag of DE film. Under activation, the film expands and the balloon grows in volume.

**Unidirectional deformation:**

For the application of soft dielectric EAPs as shell-like actuators, selective active elongation of the membrane in either the one or the other planar direction may be required to achieve complex out-of-plane displacements. Apart from preventing the active elongation of soft dielectric EAPs, their active motions can be controlled by an appropriate design of the supporting structure as well. Approaches have been focused to persistently reduce or fully prevent the active expansion of the DE film in one planar direction and to allow the deformation in the other direction. According to literature, there exist two main approaches:

(i) Anisotropic film or electrode: When the dielectric film and/or the electrode has an intrinsic anisotropic mechanical behaviour in the planar directions, more active elongation is expected in the direction with lower stiffness. For instance, anisotropic behaviour may be achieved with structured electrodes which consist of stiff (but highly electrically conductive) and compliant zones [18].

(ii) Asymmetrical pre-straining of the dielectric film: According to Pelrine et al., an asymmetrically pre-strained ($\lambda^{(i)}_x \neq \lambda^{(i)}_y$) planar DE actuator exhibits the largest active elongations perpendicular to the direction with greatest pre-strain [1]. Kovacs et al. have verified the same effect for rolled actuators, where larger axial elongations were achieved for the more circumferentially pre-strained films [17].

## 2-2. Some implemented Applications

### 2-2-1. Upper Arm Robot (Arm Wrestling Robot)

The most recognized expanding actuator is represented by the rolled actuators with a DE film wrapped around a pre-loaded coil spring, [16, 6] for driving small walking bug robots, large human like upper arm robots with high force execution [20] and acoustic filters [21].

**Figure 8.** Schematic depiction of the rolled actuator (left). Rolled actuators in different size (right)

The development of the Empa made arm wrestling robot in 2004 [17] has produced a major contribution to the production technology of expanding actuators in rolled configuration. For the arm wrestling competition at the SPIE conference in San Diego 2005 this arm robot has demonstrated the capability of EAP actuators to be used in a system which can produce remarkable mechanical work, similar to a human arm. Due to the expanding actuation characteristic an agonist- antagonistic arrangement of the actuators was necessary to produce a bidirectional motion. In this configuration all actuators were fixed in a pre-strained state in order to execute the required contracting motion under external tensile force in the deactivated mode.

**Figure 9.** The four actuator banks (left) placed inside of the arm wrestling robot (right)

The here presented expanding actuator configuration represents one basic design for any DE propelled machine to produce mechanical work in closed loop mode. When assembling the robot all actuators of the two actuator groups are mounted in pre-strained state with 30% elongation. In this neutral position (when all actuators are deactivated) the device (robots arm) is situated in the centre of the actuation range (at $45^0$ excursion state from horizontal plane) at position #0. When the actuator bloc 1 is activated expanding motion of the corresponding actuators occurs and the robot turns to the upright starting position #1 and is now ready for the wrestling action.

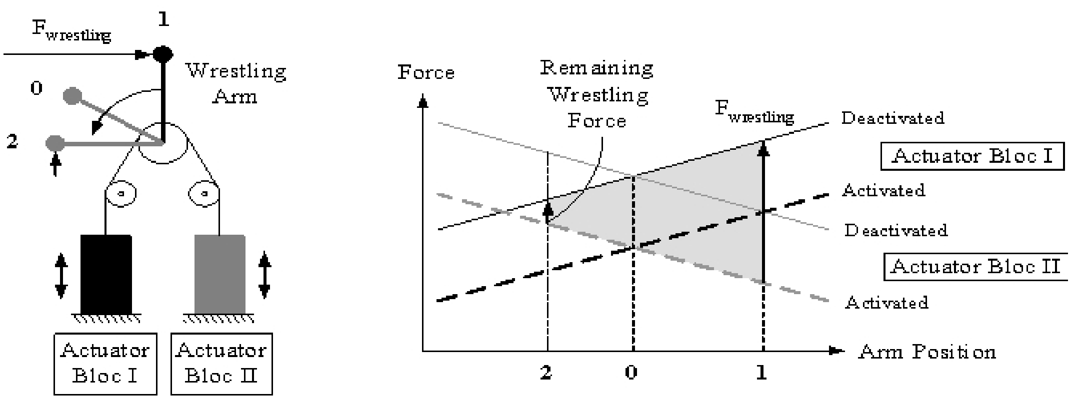


**Figure 10.** Working principle of the actuator banks and the robot arm

The maximum wrestling force $F_{res}$ at position #1 can be produced by activation of bloc 2 and simultaneous deactivation of bloc 1. The resulting motion depends on the reaction force of the human opponent. If the external force is lower than the maximum produced force of the actuators the robot arm executes the expected motion from the starting position #1 to the final position #2. Due to the elastic property of the actuators the remaining wrestling force at the end position 2 is remarkably smaller than the starting force at position 1. This decreasing trend of the resulting force was compensated by an implemented variable power gear ratio device.

2-2-2. Shell like Actuator

The shell-like actuator based on soft dielectric EAP is a shell actuator (large planar dimensions) in the macro-scale with continuous surfaces, which is lightweight and can actively exhibit large, quasi- or fully continuous out-of-plane deflections. In addition, the shell is supposed to be capable to withstand external loads acting to its surface. Regarding its structure, highly integrated solutions with low mechanical complexity, which consist of commercially available components, are preferred. According to the requirements, the shell-like actuators are capable to actively take complex out-of-plane shapes. In general, the deformation capabilities of shell-like actuators may be classified into uniaxial deformation, biaxial deformation and complex multiaxial deformation.

As an inspiration for shell-like structures, it is worthwhile to consider evolutionarily optimized approaches from nature. Batoid fishes (stingrays, skates, sawfishes and guitar fishes) for instance have wing-like bodies, which they use as propulsor. The wings of batoid fishes are mechanically braced by a skeletal system of serially arranged jointed radial bones. Muscles are spanned from the pectoral girdle to each radial bone segment. The major tasks taken by the skeletal system are:

- Generating the needed structural stiffness to transfer the forces from the surrounding fluid as well as the internal muscle forces to the pectoral girdle.
- Maintaining the wing flexibility so that large deformations of the wing are possible.

With this configuration quasi-continuous bending motions can be perform with their wings.

In contrast to the natural solution, where all muscles are connected to the pectoral girdle, independent segments each driven by a pair of pre-strained actuators are proposed [22-24]. The proposed configuration is similar to the structure of a human arm, where two natural muscles are pre-strained via jointed bones (fig.11 left). With the active segment, two pre-strained DE films are mounted to a hinged support structure (Fig. 11, centre). Under active expansion of each one of the pre-strained DE films the support structure executes a rotational deflection (fig.11 right). Thereby, the directions of motion of a natural arm and the DE configuration are opposite to each other since a biological muscle contracts under activation, while a DE actuator expands.

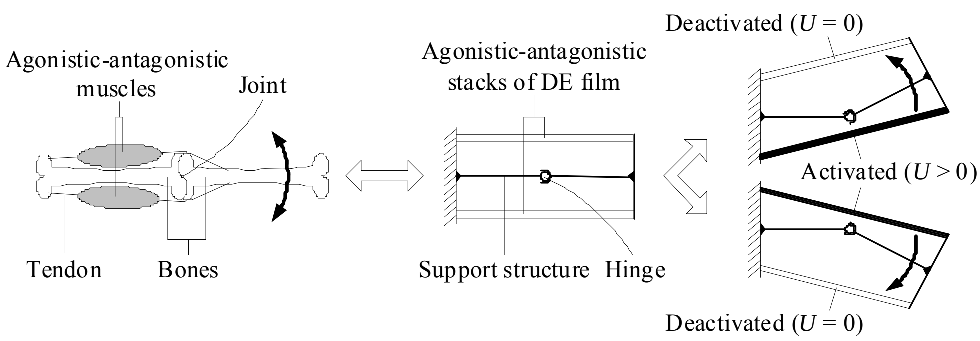


**Figure 11.** Biologically inspired agonist-antagonist configuration driven by soft dielectric EAP

The angle of deflection achieved by the active segment can be optimized by variation of the segment geometry (aspect ratio and position of the hinge joint) and the setup of the DE actuators (pre-stretch ratios). The generated deflection force, on the other hand, can be scaled by mounting stacked DE film layers to the support structure. The basic working principle to execute mechanical work is very similar to arm wrestling robot described in 2.1.1. Based on the agonist-antagonist working principle many different shell-like actuators have been developed and presented in [25]. Just to give an idea of the active shell potential one of the most impressing active shell is depicted in fig 12. In collaboration with the TU Berlin the worldwide first blimp (airship) controlled by DE propelled flaps was developed at the Empa [26]. This lighter-than-air vehicle was equipped with EAP actuators named “active hinge” driving a classical cross tail with two vertical and horizontal rudders for flight control placed between the control surfaces and the rudders. Due to this very light weight and smooth actuator’s design satisfactory flight control performance was demonstrated.

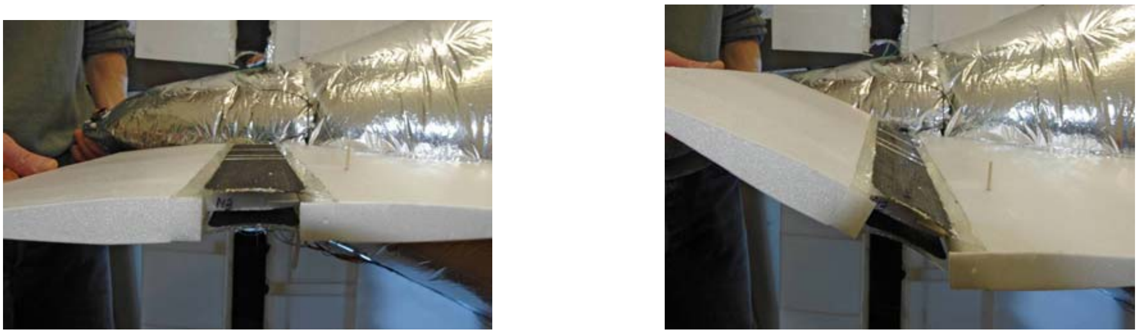

**Figure 12.** Active flap of the blimp consisting of an active hinge placed between the rudder and the control surface of the horizontal stabilizer: Passive (left) - active (right)

2-2-3. Manufacturing process

To assure a constant quality level of the actuators and to obtain the foreseen manufacturing output rate (2 actuators / hour) an appropriate fabrication facility was developed and established at Empa. Investigations have shown that the deposition of small particles (e.g. dust) on the dielectric film may essentially reduce its electrical breakdown strength. In order to prevent such potential failure, the entire fabrication facility was installed in a dust-free room to avoid any contamination of the film while producing the actuator.

The manufacturing process for the fabrication of the rolled DE actuators consists of five main steps. Thereby, for each manufacturing sequence a separate machine was built to support the process (Fig. 13). Some of them are fully automated, while others just support the manual work.

**Figure 13.** Film pre-stretching machine (left) – rolling process of the pre-strained film (right)

- Preparation of the elastic core of the actuator: The core of the actuator is equipped with fixing devices at both ends in order to fasten the stretched dielectric film to the core and finally to assure the external load introduction to the film.
- Pre-straining of the dielectric film: This process was enabled by the pre-stretching machine, which was specifically developed at Empa, to produce the actuators in limited lot production. After the pre-stretching process the film was fixed to a stiff plate in order to “freeze” the film in its pre-strained state for the further production sequences.
- Coating of the pre-stretched dielectric film: Carbon powder mixed with silicone oil was used for the conducting electrodes. Thin aluminium stripes were added to the longitudinal fringe of the film to perform the high voltage contacting. Each rolled DE actuator consists

of a stack of two coated and pre-stretched films.

- Wrapping of the coated dielectric film around the core: During the wrapping process it is of essential importance to maintain the stretched state of the film. This production step was supported by a wrapping setup.
- Sealing of both actuator ends: The ends of the wrapped actuator were sealed to enable the transmission of the external loads to the wrapped film.

Unfortunately most highly pre-strained actuators with high actuation performance in planar direction have poor long-term lifetime due to the high pre-stretching in combination with the necessary rigid supporting structure. For this reason only a limited number of applications based on planar actuation mode and using (asymmetric) highly pre-strained film may be considered. As it can be observed in the field of completed devices pre-straining can only be applied when the film is continuously fixed to a rigid frame with circle like shape (circle actuator) to avoid any local stress concentration.

## 3. CONTRACTIVE STACK ACTUATOR

When contraction at activation is required the well known "expanding planar EAP actuator" does not represent the appropriate solution for many applications. For this reason new actuators in pile-up design are proposed which exhibit contractive deformation under electrical activation.

Based on the folded and helical design with non-pre-strained silicone film contractive motion of the actuator has been demonstrated [27]. This actuator consists of a single strip of an elastomer that is first coated with compliant electrodes and then folded up, so as to form a monolithic compact body. The folded structure is finally 'sealed' with a thin coating made of the same elastomer used for the strip. A high voltage applied between the electrodes causes a thickness squeezing of the entire elastomeric layer which results in an axial contraction of the overall structure.

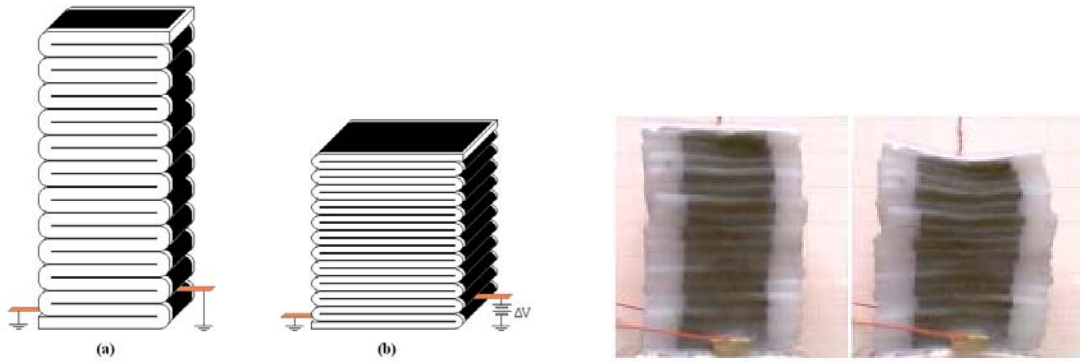


**Figure 14.** Principle of the Contractive folded actuators (Courtesy of University of Pisa, School of Engineering)

Furthermore the basic design of the stack configuration has been developed and demonstrated for electrostatic tactile displays with high structural compliance [28]. When a voltage is applied between neighbouring electrode layers of this device, the actuator stack will contract and the stimulator tip will disappear below the surface of the device.

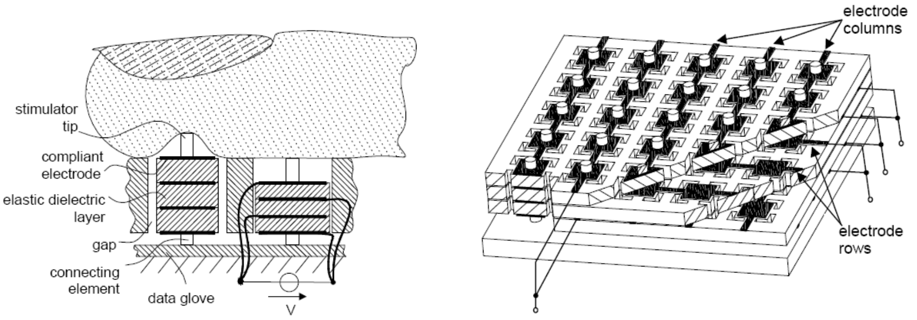


**Figure 15.** Structure and function of an electrostatic tactile stimulator with elastic dielectric (left) - Planar stimulator arrangement for a tactile display (right) (Courtesy of Institute of Electromechanical Design / Darmstadt University of Technology).

Due to the application requirements the actuators are either free of any external force or are loaded by external pressure force produced by the finger tip. Thus this actuator is not designed for taking external tension force.

The as next presented novel contractive stack actuator has the capability to take external tension force which represents the key feature for a wide range of application.

The new actuator consists of many small pieces of dielectric elastomer films coated with compliant electrodes and layered in serial configuration (fig. 16). For activation a voltage source is connected to the electrodes. The resulting electrostatic force presses the electrode particles against the polymer film, which therefore is squeezed. The thickness decreases, whereas the film expands in planar direction due to the fact that DE film is almost incompressible. On deactivation the electrodes are short circuited and therefore discharged. The electrostatic force disappears and as a result the polymer film expands back to its original film thickness. Due to the fact that the actuation direction is parallel to the electrostatic field lines and therefore normal to the plane of the electrode / dielectric film the electrostatic force can directly be turned into specific mechanical service force to drive the device. The as compressed DE film produces the contraction motion of all layers and therefore of the entire actuator. To provide the tensile force transmission from one DE layer to the next the electrode design with anisotropic property plays a central role and represents a novelty in the field of soft dielectric EAP actuators. Thereby solid materials tension stress in the electrode is produced by the electro-static field in normal direction whereas the compliancy in planar direction has to be assured in order to enable the required planar deformation. In this configuration the dielectric film sandwiched between two electrodes takes the function of a "spacer" and does not contribute to the actuation force in transversal direction. As a result the film is solely compressed when voltage is applied and does not take any tensile stress in transversal direction which is an important issue concerning strength and fatigue behaviour of the film and therefore of the entire actuator.

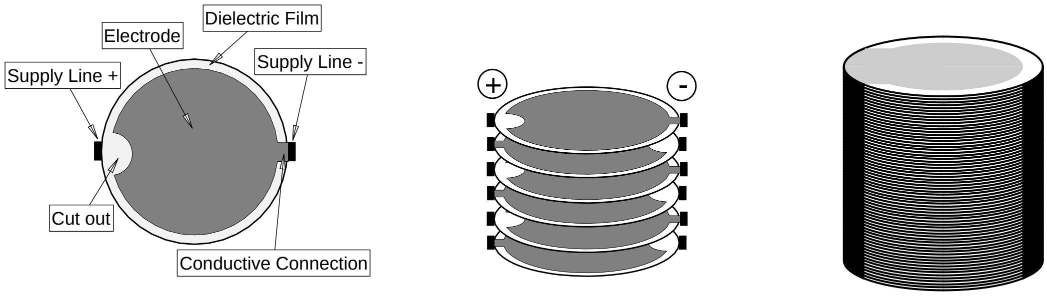


**Figure 16.** Stacked configuration of dielectric elastomer layers

To apply the activation voltage to the electrodes, they have to be alternately connected to the voltage source. Thereto each electrode has an appendix to the border of the layer. Alternating polarities can be achieved by arranging the layers in alternating alignment mode of the appendices when piled up. In this configuration the force producing electrostatic fields of each layer are switched in series whereas the capacitors are electrically switched in parallel with essential impact on the low electric resistance of the entire system. The appendices are connected with a compliant conductive band placed on two opposite side face of the actuator addressing the associated conductive layers.

**Most important design parameters:**

- The number of added layers affects the length of the actuator and therefore the absolute contraction length when activated. Based on the produced electrostatic pressure the absolute exhibited force is determined by the area of one piece of dielectric elastomer film. Adding a large number of equal elastomer and electrode layers an actuator in the macro scale can be produced.
- To avoid electric breakdown at the side surface between the electrodes, an uncoated boarder area is necessary (fig. 16). As a result a loss of electro active area has to be considered, which generally reduces the effectiveness of the actuator. Therefore the width of the passive boarder has to be designed as small as possible in order to obtain maximum performance.
- Due to the anisotropic electrode stiffness property the contractive actuator is supposed to take external tension force. This force has to be introduced into both ends of the actuator which requires appropriate end fixing parts consisting of solid material. The interface between the soft actuator material and the stiff end fixing part leads to a locally complex stress state of DE material. As a matter of fact the actuator performance potential is reduced within the transitional zone with limited deformation capability.

In order to demonstrate the design parameter dependency of the actuation performance and the deformation potential respectively five actuators with circular punched layers at different design and size are presented. The dimensions of the actuators are described in the following table 1.

| Actuator | Total diameter | Active diameter | Height | Number of layers |
|---|---|---|---|---|
| 1 | 18mm | 16mm | 18.3mm | Ca. 280 |
| 2 | 20mm | 16mm | 21.2mm | Ca.330 |
| 3 | 20mm | 16mm | 14.0mm | Ca. 210 |
| 4 | 20mm | 16mm | 22.9mm | Ca. 350 |
| 5 | 20mm | 16mm | 25.8mm | Ca. 400 |

**Table 1.** Key data of the characterized actuators

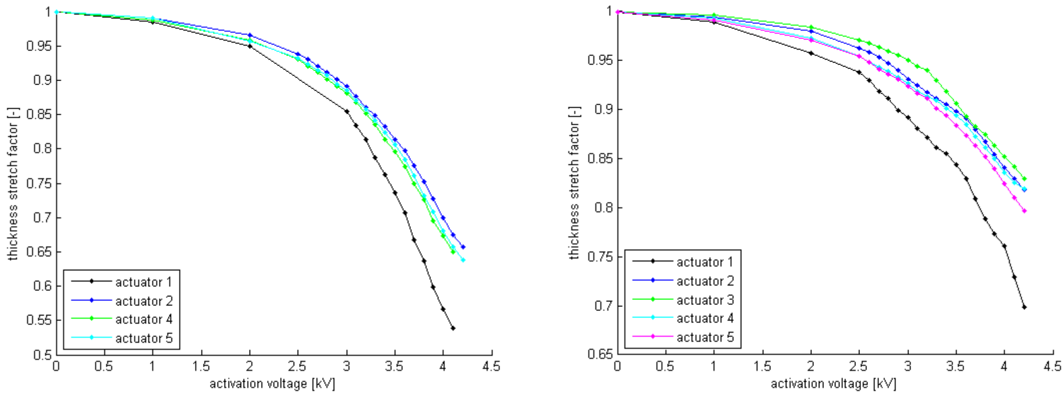


**Figure 17.** Contractive deformation of the free end (left) and fixed end (right) actuators

As expected fig. 17 left reveals the performance dependency of the passive / active area ratio as the most relevant design parameter. The maximal measured contraction for free end actuators was 46% at an activation voltage of 4.1kV. This was achieved with actuator #1 which has the smallest amount of passive area (21%). The other actuators reached a contraction up to 35% at even higher activation voltage of 4.2kV.

The maximal measured contraction for fixed end actuators was 30% at an activation voltage of 4.2kV achieved by actuator #1 (fig. 15 right). The other actuators reached a contraction up to 20% at the same activation voltage of 4.2kV.

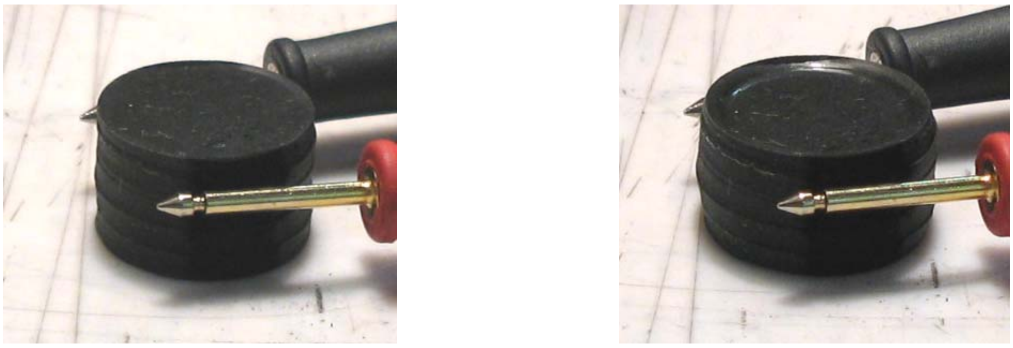

**Figure 18.** DE stack actuator with free end: deactivated (left) – activated (right)

**Figure 19.** DE stack actuator equipped with fixed end parts: deactivated (left) – activated (right)

The difference in maximal contraction between free end and fixed end actuators is significant. For a DE stack actuator with a larger length to width ratio and a smaller amount of passive border area to total cross sectional area a smaller difference is expected.

3-1-2. Manufacturing process

Due to the pile-up design of many small DE layers no pre-strained film equipped with the necessary strain supporting structure can be processed in a useful manner. However, the pre-stretching stress has to be essentially reduced or more likely eliminated to obtain a stack actuator with acceptable specific performance. This has been achieved by introducing trifunctional methacrylate monomers (Trimethylopropane Trimethacrylate TMPTMA + Dibenzoylperoxid) into the highly pre-strained acrylic films and subsequently curing the monomers to form an interpenetrating elastomeric network [29]. The as obtained interpenetrating polymer network (IPN) can effectively support the pre-strain of the acrylic film and consequently eliminate the need for external pre-strain-supporting structures. The IPN composite films without externally enforced pre-strain exhibit electrically induced strains of up to 233% in area expansion [29]. Due to this very promising result all EAP stack actuator are made with IPN post-processed VHB 4910 films.

As electrode material pure Ketjenblack KJ-600 graphite powder has been established for all types of EAP actuators made by adhesive films. The powder is smeared on the sticky surface of the film. The thickness of the applied coating is in the sub-micrometer range. Due to the very low thickness of the electrode and its planar compliancy the stiffening effect of the film is negligible.

The quality of the stack actuator in terms of actuation performance essentially depends on the appropriate pile-up manufacturing process. Basically many small and coated DE film pieces have to be assembled in a stack configuration. Thereby high accuracy of the coating, cutting and pile-up process is of paramount importance to avoid any local breakdown effects when in use. Two different favourable methods have been evaluated and established to produce stack actuators.

**Parallel processing (Handcrafted)**

In general large units of DE film can be used for coating many small actuators at once. By stacking a low number of these films (in the range of 10 pieces) many actuator layers can be produced in a few process steps. Thereby each film is coated with electrode material by using a mask which defines the shape, size, location and finally the number of pieces representing the actuator modules. The final assembling (stacking) of all multilayer modules can be accomplished after having cut out each piece. This parallel mode manufacturing process has been evaluated as the appropriate handcrafted manufacturing method.

**Figure 20.** Intermediate steps of the handcrafted manufacturing method with parallel processing

**Batch processing (automated facility)**

For most manufacturing activities on industrial level, however, a fully automated process is strongly preferred. For this reason a prototype machine was developed and set up to produce stack actuators in a fully automated mode as next step. To demonstrate the feasibility of an automated DE actuator fabrication the present “stacker” machine has been developed at Empa.

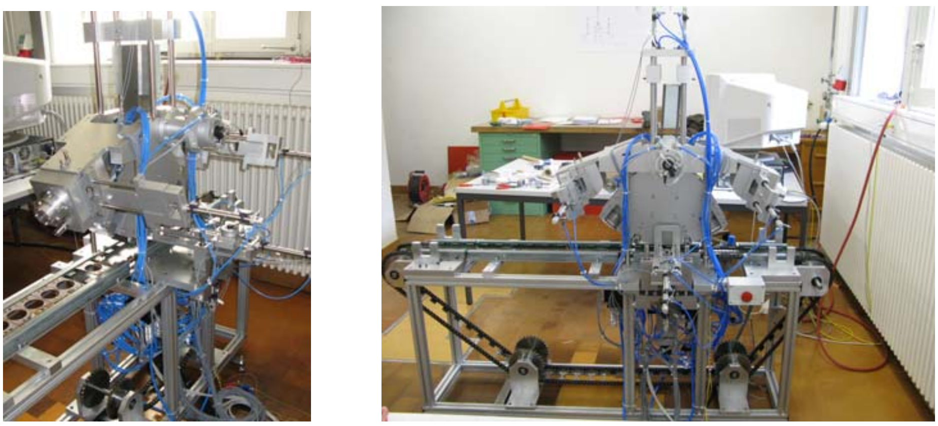

**Figure 21.** Fully automated stack actuator manufacturing machine “stacker”

Thereby the actuator is produced by stacking and coating DE films layer by layer. Using this method the actuator is “growing” up to the required size (length) at given cross sectional size (max. 50mm diameter) and shape. In contrast to the handcrafted method high repeatability and constant manufacturing quality can be provided by using the stacker machine with repeating process cycles.

## 4. CONCLUSIONS

Many different DE actuator systems have been developed and presented based on expanding membranes with high deformation performance. As one of the most recognized DE actuator system the arm wrestling robot driven by many rolled actuators producing high actuation power has demonstrated the application potential of the DE working principle as artificial muscle. On the one hand it was proved that the DE driven robot has executed the bidirectional rotary motion and exhibited the required wrestling force. On the other hand the applied expanding actuator design has revealed the weakness of the pre-strained DE film. Due to the stress concentration at the interface between soft polymer film and rigid supporting structure mechanical failure of most expanding membrane actuator occurs. Moreover the actuator's functionality is therefore essentially limited. Insufficient reliability, unpredictable long term failure behaviour and limited actuation modes have been observed and are the consequences thereof which have to be eliminated for most applications. As a matter of fact the present design of the expanding actuator is essentially influenced by the remaining pre-strain conditions. In order to overcome the above mentioned problems the inherent stress has to be reduced or new materials with low relaxation properties have to be evaluated.

In contrast to the expanding planar actuator in different configurations, the contractive stack actuator demonstrates the feasibility and convenience of the pile-up configuration for many applications where contraction at activation and tensile force generation is of central interest. Thanks to the resulting contracting effect under external tensile load the present design can be denoted as artificial muscle with mechanical properties very similar to natural muscles. Furthermore a new generation of material system may be expected where the structural integrity is governed by the Maxwell forces produced by the electro-static field. Due to the absence of any tensile stress in the DE film when activated an overall good operational stability and endurance strength can be observed which has a beneficial impact on the long term reliability of the actuator. For this reason an emerging exploitation of this new generation of DE actuator can be expected in the near future.

For most application with bidirectional motion requirement agonist-antagonist actuator system is preferred. In this case the combination of expanding actuators as antagonist and contractive actuators as agonist may represent a favourable configuration. Once the problematic long term failure behaviour of the pre-strained DE film will be overcome the combined actuator system may find its path into the robotic world for producing mechanical work in a soft and noise free mode.

Due to the general need of an essentially lower actuation voltage (matter of electronic amplifier expense), tailor made elastomers with high dielectric constants and good overall electro-mechanical properties are key issues for practical applications. Enhancing the material's dielectric constant and reducing the thickness of the elastomeric film applied in a dielectric actuator allow us to reduce the voltage necessary to drive such devices to values in the range of 500V.

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