Novel Actuators for Haptic Displays based on Electroactive Polymers

Andrea Mazzone
Center for Product Development
Swiss Federal Institute of Technology
Zurich, Switzerland
mazzone@imes.mavt.ethz.ch

Rui Zhang
Center for Product Development
Swiss Federal Institute of Technology
Zurich, Switzerland
zhang@imes.mavt.ethz.ch

Andreas Kunz
Center for Product Development
Swiss Federal Institute of Technology
Zurich, Switzerland
kunz@imes.mavt.ethz.ch

ABSTRACT
After a wrap-up in the human physiology and an overview on physical principles, this paper introduces four novel types of actuators for haptic feedback devices based on electroactive polymers, which were developed and evaluated for their suitability for haptic feedback devices. The electroactive polymers show many promising properties, such as big expansion, high frequency range and big force exertion for instance. Unfortunately they are still in the fledgling state and are not available on the market yet. The actuators presented in this paper are a contribution to the haptic and to the electro active polymer researchers community.

Keywords
Haptic displays, force feedback, actuators, human factors, smart materials, electroactive polymers

1. INTRODUCTION
Compared to video and auditory components of augmented and virtual reality systems, haptic feedback devices are still in the fledgling stage. In fact, only small advances have been made in that field and today's state of the art haptic interfaces show different constraints and disadvantages for general haptic feedback applications. This is due to several factors, though they are crystallisable firstly into the complexity of the human anatomy and its dexterity of the tactile sense and secondly into the inappropriate properties of the state of the art actuators.

Basically, two types of haptic interfaces can be distinguished. The grounded devices and the portable ones [1]. Most of them were developed for dedicated tasks and fulfill their requirements quite well. For general applications however, both types present some drawbacks, which often are typical trade-off problems between frequency and force exertion range; thus sensitivity (high resolution) versus high force, high momentum and big translation.

These factors are directly connected to the mechanical characteristics of the state of the art actuators. In order to be able to develop lighter and more comfortable haptic feedback devices, further research efforts have to be done in the field of actuation technology. Actuators with higher energy density and with smaller overall sizes are required. The actuators presented in this paper veer toward it by being based on electroactive polymers. These Smart Materials show many promising properties, that, successfully integrated into a novel haptic feedback device, would enhance the quality of the haptic feedback sensation.

In order to best adapt the interface to the human haptic channel, some general investigations on haptic perception have been done firstly, which resulted in a requirements list for haptic actuators.

2. TOUCH AND SENSING
Five major senses can be distinguished: vision, hearing, smell, taste and touch. Touch can be defined as the sensation evoked by mechanical, thermal, chemical or electrical stimulation of the skin and body. The sense of touch relies on *cutaneous* and *proprioceptive senses*. Tactile (cutaneous) information is conveyed by specialized receptors through spatial and temporal variations of the force distributions within the contact region on the skin. The proprioceptive sense has two submodalities: the *limb position sense* refers to the awareness of the stationary limb position while *kinesthesia* refers to the sense of limb and body movement [4].

The most interesting fact is that the inputs of the peripheral regions are systematically mapped onto structures of the brain and their sizes reflect the importance of the particular areas. Thus the finger tips or for example the lips are represented by a large area in the brain, whereas the skin of the back has a small corresponding area.

2.1 Physiology
Four distinct somatic modalities (the physical property of a stimulus that activates a receptor is called its modality) are known:

- *Touch*, elicited by mechanical stimulation of the skin.
- *Proprioceptive sensations*, elicited by mechanical displacements of the muscles and joints.
- *Pain*, elicited by noxious (tissue damaging) stimuli.
- *Thermal sensation*, elicited by cool and warm stimuli.

These elementary modalities can further be split in submodalities. So we can distinguish several forms of tactile sensation, such as pressure and vibrations for example but also two forms of limb proprioception (static: position sense and dynamic: kinesthesia). Thus sensations can have their origin in any of these modalities or submodalities but also in a combination of both such as for example the sensation of wetness.

2.2 Mechanoreceptors

Mechanoreceptors are responsible for touch sensation. Five major types of receptors can be found in the remarkably discriminating glabrous skin while a sixth covers the hairy skin; the hair follicle. Table 1 summarizes the most important characteristics, omitting two of them for simplification. As already mentioned, the receptors differ also in their size.

Receptors	**Meissner Corpuscles**	**Merkel's Disks**	**Pacinian Corpuscles**	**Ruffini Corpuscles**
Location	Glabrous skin; Dermis	Glabrous skin; Epidermis	Glabrous and hairy skin; Dermis and subcutanous	Glabrous and hairy skin; Dermis and subcutaneous
Adaptation rate	Rapid; RA-I	Slow; SA-I	Rapid; RA-II	Slow; SA-II
Receptive field	Small $12mm^2$	Small $12mm^2$	Large $100mm^2$	Large $60mm^2$
Frequency range	20-100Hz	0-10Hz	100Hz-1kHz	0-10Hz
Best response	30-40Hz	0-10Hz	150-130Hz	0-10Hz
Proportion	40%	25%	13%	19%
Function	Movement, Velocity	Pressure, Vibration	Acceleration, Pressure	Pressure, Skin shear, Thermal changes

Table 1: Characteristics of Mechanoreceptors

The size of the receptive field delimits the capacity of the receptors to resolve spatial detail of objects. Thus **spatial resolution** can be used as another way to characterize the receptors. Its range starts from 1-2mm^2 and goes up to 45cm^2 depending on the receptor and the location on the body.

Mechanoreceptor have also a **temporal resolution** of approximately 5msec which is five time smaller than the one of the eye (25msec) [1].

2.3 Muscle Afferent Fibers

Muscle Afferent Fibers are the source of the sense of position and movement of the limbs, which are important sensations for maintaining balance or controlling limb movements for instance. Two submodalities are known in proprioception: the stationary position sense and the kinesthesia (sense of limb movements). Position is sensed through the angles of skeletal joints, while motion is detected through change in angle per unit of time (velocity - movement). The accuracy of position detection is quite high, starting from a maximum of 0.2° (hip joint) to a minimum of 6.1° degrees (toe) [Kalawsky, 1993].

2.4 Nociceptors

Nociceptors are triggered by tissue-damaging stimuli and provide the sensation of pain. Three different kinds of receptors are responsible for detecting the different kinds of stimuli. Strong mechanical stimulation, such as sharp objects, are detected by mechanical nociceptors, while thermal nociceptors respond to heat or cold. The third kind includes the polymodal nociceptors which respond to several different kinds of noxious stimuli, such as mechanical, heat and chemical [4].

2.5 Thermoreceptors

Thermoreceptors are responsible for the thermal sensation and can be divided in those preferentially receptive to cold and those receptive to warmth. The sensitivity is punctuate: The receptive fields are approximately 1 to 2mm in diameter and have a density of 1 to 5 cold-sensitive receptors/cm^2 and a density of 0.4 receptors/cm^2 for warmth-sensitivity [4].

2.6 Hand and finger

The hand plays an indispensable role in our everyday's life. Thus, a large area is reserved in the cortex for sensory processing as well as for motor control. The skin of the fingers is one of the most sensitive with up to 135 receptors per square centimeters at the finger tip. In addition, fingers are sensitive for vibrations up to 1kHz giving the ability to feel and sense different type of textures. However, they are most sensitive at approximately 230Hz. Above this frequency stimuli are sensed as vibrations.

Motor control, similar to sensory control, plays another very important role. Since in the early years human make use of their hands to explore the surrounding, shape and texture detection are dominant in the control loop. Connected to motor control as well as to the sensory control is the force exertion control mechanism. Sensory feedback is used to control the activity as for example grasping by minimizing in the same time the applied force. Force is regulated in real time depending on the object's surface, weight, resistance, etc.. Cutkosky and Howe (1990) have divided the grasp in two categories:

- **The power grasp**, which has high force and stability as the whole hand (palm included) is used. However, the power grasp is limited in accuracy and in dexterity, because the fingers are locked tightly around the object.
- **The precision grasp** uses mostly the fingers achieving a much higher accuracy. Here dexterity and skill play an important role and can enhance the precision significantly.

2.7 Force Exertion

The force exertion on fingers and hand can be measured in many different ways, depending on the location where it is applied but also on the time range. Latter is a very important point that should not get forgotten. Maximal force can be exerted only for a short period of time. Thereafter fatigue and discomfort are complaint which involves also sensorial control that decreases in accuracy. Exaggerated activities can lead to pain but also to injuries.

Studies have found that males can exert power grasps of maximal 400N, while females reach 230N [An et al. 1986]. Maximum forces on individual fingers instead should not exceed 30-50N. Tests showed, that the pointer and index finger can exert 50N while 40N is the maximum for the ring finger.

2.8 Requirements for haptic feedback

For a complete and realistic haptic feedback, all modalities (touch, proprioceptive, pain and thermal) have to be simulated. To achieve this, hybrid systems are necessary, which integrate force and tactile feedback devices with pain and temperature simulating devices in one haptic feedback system. The most important requirements to haptic feedback are listed in Table 2.

Requirements	
Working frequency	$> 230Hz$
Force exertion for haptic feedback device	$> 10N$
Spatial resolution for (texture recognition)	$\sim 1mm^2$
Elongation	$< 10\%$
Temperature sensation	$0° - 45°C$

Table 2: Requirements for a haptic feedback device for the hand

3. PHYSICAL PRINCIPLES

Touch is felt, when a force is applied to the skin. The force may be of constant strength, but also vibrating. It may be moving, scratching or jumping over the body surface. The contact region may be one single point or a complete surface. Simulating haptic sensations directly via a connection to the nerves is still science fiction, even though several experiments were and are done in research labs. For general haptic feedback in virtual environments however, it is not imaginable to insert any kind of probe or connector to the user's body.

Thus, if no other systems are found to interface with the nerves directly, then the haptic feedback has to be implemented by applying forces to the skin at the according position, in a defined direction, with a defined strength and with a defined frequency.

3.1 The Principles and the Evaluation

An extensive study and evaluation has been done and almost fifty physical principles were investigated with 'force' as a physical value or variable. Following is a short selection: gravitation, acceleration, impulse, angular momentum, buoyant force, centrifugal force, centripetal force, force of coriolis, jet pressure, rebound, convective acceleration, force of coulomb, capacitor effect, osmosis, smart materials, spring, electro- and magnetostriction, dielectric materials in inhomogeneous and homogeneous electric fields, etc.

These principles were evaluated using following criteria: Feasibility, possible technical implementation, magnitude of force generation, range of force exertion, frequency response, diversification (small range of exertion - small forces, big range of exertion - big forces) and dynamic range. The benchmark was as follows: 1 for insufficient, 2 for sufficient, 3 for good and 4 for excellent. In addition, weighting was used on the criteria to give more or less importance to them. 10% for feasibility together with possible technical implementation, 30% for the magnitude of force generation, 15% for the range of force exertion, 20% for the frequency response, another 15% for diversification and last but not least 10% for the dynamic.

The evaluation resulted in the following ranking list:

1. Spring force
2. Magnetostriction
3. Electrostriction
4. Electro rheological fluids
5. Magneto rheological fluids

The evaluation clearly shows, that with the exception of the spring, the so called smart materials top the ranking list. Thus a closer look on the materials is required.

4. SMART MATERIALS

Terms, such as 'smart materials', 'smart structures' and 'adaptive structures' arose in the eighties of the last century in the USA and in Japan and became more and more popular. Today, these terms are used to pool materials such as piezo, shape memory alloys, electro- and magneto rheological fluids, electro- and magneto restrictive materials, etc.. They have the capability to sense and to measure, but also to process and to act having variables, such as deformation, temperature, pressure, and changes in state and phase, and may be optical, electrical, magnetic, chemical, or biological [6].

In the following subsections, some of the smart materials will shortly be introduced, contemporarily bridging them to their use in the field of haptic feedback.

4.1 Piezo Materials

Piezo materials have some properties that can be of big use for feedback of tactile information. By applying a high voltage the crystals change their shape. Accompanied by huge forces, translation can be achieved this way. Their disadvantages for haptic feedback applications are the tiny translations of a few μm. On the other hand, vibration around 1kHz (max. sensible frequency by the human) can be achieved without any problems. Tactile feedback is feasible, thus simulations of different texture are possible.

Actuator Typ	EAP	SMA	Piezo	ERF	MRF	Electro-magnet	Human muscle
Strain %	>10%	<8%	0.2	NA	NA	50%	>40
Force MPa	0.1-3	700	110	$2\text{-}4*10^{-3}$	$60\text{-}120*10^{-3}$	0.1	0.35
Reaction speed	ms-min	s-min	µs-s	ms	ms	ms	s
Energy density J/cm^3	0.3-3.4	>100	0.1	NA	NA	0.025	0.07
Density g/cm^3	1-2.5	5-6	7-8	1-2	2-3	NA	NA
Drive voltage	2-7V/µm 10-150V/µm	not applicable	< 200V	4kV/mm	not applicable	not applicable	Neutral activation

Table 3: Overview of the physical parameters of different smart materials

4.2 Shape Memory Alloys

Shape Memory Alloys (SMAs) belong to that group of metallic materials that demonstrate the ability to return to some previously defined shape when subjected to the appropriated thermal procedure. When SMAs encounter resistances during this transformation, they can generate large forces, which would be of great advantage for force feedback devices. The most two common SMAs available on the market are the NiTi or the copper-based alloys. A wide variety of applications can be found in free or constrained recovery, force actuators, proportional control, superelastic applications, etc.. SMAs can produce much more useful work per unit volume than most actuating mechanisms; however, one must take into account the forces, displacements, temperature conditions, and circle rates required by a particular actuator. Unfortunately their long relaxation time (seconds to minute) make them useless for most haptic feedback tasks.

4.3 Electro Rheological Fluids

Electro Rheological Fluids (ERFs) offer some possibilities as well. By applying an electric field on the fluid a change in its viscosity can be observed [2],[3]. This effect could be used for haptic feedback devices. Very small actuators could be developed that could be integrated into gloves. However, the smaller the device is, the smaller is the shear stress that can be achieved. In addition, high voltage is needed (around 2-4kV per millimeter gap between the electrodes) with the consequence that safety aspects have seriously to be taken into consideration. Some advantages are the achievable high frequencies around 1kHz and the high shear stress around 2-4kPa. On the other hand, there are some disadvantages, such as sedimentation for instance, that have to be eliminated as much as possible.

4.4 Magneto Rheological Fluids

Magneto Rheological Fluids (MRFs) show the same effect in a magnetic field, as the ERF do in the electric field: A change of viscosity is observed while the field is on. MRF reach much more higher shear stress (around 60-120kPa) than ERF. The magnetic fields needed are likewise high and represent among other things (such as sedimentation and abrasiveness for instance) the disadvantage of the MRF for wearable haptic feedback devices since relative big solenoids are necessary.

4.5 Electro Active Polymers

Electro Active Polymers (EAPs) exhibit a significant shape or size change in response to an electrical stimulation [5]. EAPs are often called "Artificial Muscles" since they behave similar to biological muscles. They are showing a superior actuation displacement, mass, cost, power consumption and fatigue characteristics over conventional actuators and other smart materials. Applications with EAPs include artificial muscles, synthetic limbs and protheses in medicine, miniature robotic arms, miniature insect-like robots and Ink-jet printers in process techniques. Thus EAPs have been chosen for the further development. Table 3 summarizes the physical parameters of different smart materials compared also to the human muscle and to an electromagnet.

5. ELECTROACTIVE POLYMERS

In the last decades, electroactive polymers (EAP) have received more and more attention by material scientists as well as by application engineers. As one of the smart materials, EAP is light weight, highly agile, damage tolerant, has low power consumption. EAPs show a large actuation strain ($> 10\%$), a force range of 0.1 up to $3MPa$ and a relative broad range of response time ($msec\ to\ min$) [5] (see also Table 3). These attractive characteristics present great potentials for micro electromechanical systems [5]; [8], bionic robots [9] and biologically inspired technology [10]. However, the disadvantages of the electroactive polymers cannot be ignored, such as the required high voltages or the unideal polymers for instance. The important characteristics of latter have still to be completely understood. In addition, the manufacturing process is still very complicated and far away to be suited for mass production. Therefore, most of the developments stay within laboratory and only few of them are commercially available. The polymers themselves are difficult to find and just a few of them are available on the market ([11] is one supplier for example). However, we still see an opportunity to develop actuators based on EAPs that might lead to a novel haptic feed back device, which overcomes the current problems mentioned before. Concerning our application for a haptic feedback device (see also Table 2), based on both technical and economical issues (see Table 3), we prefer to use dielectric polymers, which support potentially enough actuation force, actuation strain, frequency and obviously independence of working conditions.

Actuator type		Actuation mechanism	Material	Manufacture	Activation voltage	Response time	Working condition
Ionic Polymer	Conductive Polymers (CP)	Electrochemical process: actuate via reversible counter-ion insertion and expulsion that occurs during redox cycling.	Polypyrolle(PPy), Polyaniline (PA)	Lab	1-5 V	Slow	wet, few works in air
	Ionometric Polymer-Metal Composite (IPMC)	Iontransportation throuh polymer nets between two electrode	Nafion, Flemion	Dupont, Asahi Glass Co., Lab	1-10V	Slow	wet, in air
	Ionic Polymer Gels	Diffusion of ions through polymer gels	Polyvinylacohol (PVA), Polyacrylacid (PAA)	Commercially avalaible, Lab	<10V	Slow	wet
Electric Polymers	Ferroelectric Polymers	Piezoelectricity	Poly(vinylidene fluoride(PVDF), P(VDF-TrFE)	Commercially avalaible, Lab	>1 kV	Fast	in air, vacumm, wet
	Dielectric Polymers	Electrostatic field induced Strain	Silicon elastomer	Dow, Nusil, Technik, Lab	>4kV	Fast	in air
			Acrylic elastomer	3M	>3kV	Middle	in air
			Polyurethane(PU)	Deerfield	>3kV	Fast	in air
			Polybutadiene (PBD)	Adrich	>3kV	Fast	in air

Table 4: Overview of electroactive polymers

5.1 Dielectric Polymers

As a subgroup of electroactive polymers, dielectric polymers are insulating, rubber-like structures, capable of undergoing reversible length change while contemporarily exerting forces on attached objects [12]. Thus, dielectric polymer actuators output directly linear motion which suggest their novel applications for smart structures, MEMS, and haptic feedback displays. The working principle of dielectric polymers is shown in Figure 1. When compliant electrodes are attached to both sides of a piece of elastomer and a DC $(2.5 - 3kV)$ voltage is applied, the actuator expands in planar directions, while decreasing in thickness. The actuator contracts to its original shape when the electric field is turned off. The mechanical driving force of the actuator

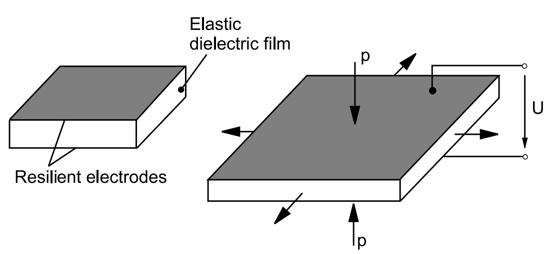


Figure 1: Simple working principle of an EAP

is the Coulomb charge attraction. Applied with the electric field, the polymer capacitor is charged. The compliance of the polymer allows the two electrodes to approach to each other by squeezing the polymer in between. As the volume always remains constant the elastomer is forced to expand transversely to the electric field. The field induced pressure can theoretically be expressed with the equation (1),

$$p = \epsilon\epsilon_0 \frac{U^2}{d^2} \tag{1}$$

where ϵ is the relative permittivity of the polymer, $\epsilon_0 = 8.854 \cdot 10^{-12} As/Vm$ is the dielectric constant, U is the applied voltage and d is the thickness of polymer.

The strain of the actuator in planar direction can be augmented by increasing the induced stress, which in turn can be achieved by increasing the electric field. The equation shows that an incrementing of the driving voltage or a reduction of the polymer thickness induce larger pressure. But practically, it is not suggested to just apply a higher voltage on the polymer. Firstly, it may cause short circuits in weaker spots in the material and secondly, for haptic feedback devices the voltage has to be kept as low as possible for security reasons. Actually the researchers are trying to reduce the necessary activation voltage by decreasing the thickness of the polymer and by increasing the dielectric constant of the materials. In order to achieve a larger induced force whereas, enlarging the electrode as much as possible is another important process.

In this study, several EAP actuators for haptic feedback applications were developed. Four of them will be introduced more in detail in the following sections.

6. EXPERIMENTS

The developed electroactive polymer actuators differ in their actuation concept as well as in their manufacturing process. So it can be distinguished between flat and cylindric actuators as well as between one dimensionally and two dimensionally pre-stretched actuators. Table 5 shows the selected combination. With the flat actuators the material actuation capabilities were investigated, while with the cylindric one their use in more complex actuator design was tested.

Adhesive transfer tapes (VHB F-9473PC) by 3M was employed as basic polymers. They show high adhesion and long term holding power in many industrial applications.

Pre-stretching \ Actuator concept	Flat actuator	Cylindric actuator
1-dim pre-stretched EAP		
2-dim pre-stretched EAP		

Table 5: One and two dimensionally pre-stretched, flat and cylindric actuators

6.1 Flat dielectric polymer actuator

Three flat actuators were developed with different pre-stretching directions and factors to investigate their influence on the actuation capabilities. The stretching factor indicates how many times the material is pre-stretched. Two actuators are one-dimensionally pre-stretched flat dielectric polymer actuators, with different pre-stretching factors, while the third one is a two-dimensionally pre-stretched actuator. The employed materials are listed in Table 6.

Terms	Material	Data
Polymer	VHB F-9473PC 3M	Thickness 0.25mm
Electrode	Graphite powder	Particle size: 90% 0.063mm, 10% 0.16mm
Contact	Zinced copper wires	Ø 1mm
Fixture	PVC plate	-

Table 6: Employed materials

The manufacturing process is briefly presented in Table 7.

1. Material preparation	2. Pre-strain	3. Electrode coating	4. Actuator build up
Material extimation Material cutting Acrylic film fixation at two ends Paper protaction off	Material pre-stretching with λ_B Taking off the middle part of the pre-stretched film	Ascertainment of electrode area Sticking of wires on both sides of the film Coating (both sides λ_B) Film relaxation to λ_A	Fixture (λ_A) Measurements setup

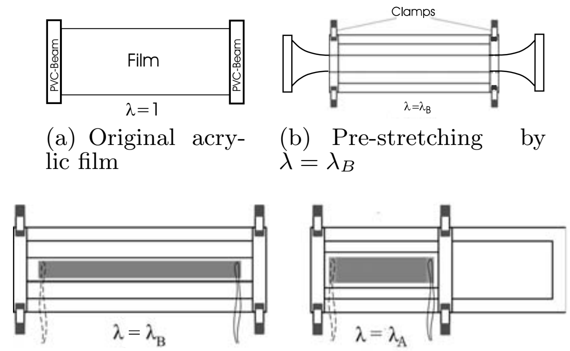
Table 7: Actuator manufacturing process

λ is the pre-stretching factor. λ_A is the pre-stretching factor during the activation process. λ_B is the pre-stretching factor during the coating process. In order to enhance the graphite powder density, the film was coated by stretching factor λ_B, and then relaxed to λ_A. The actuator itself is activated with the pre-stretching factor λ_A.

6.2 One-dimensionally pre-stretched dielectric polymer actuator

One-dimensional pre-stretching means that the film is pre-stretched along one direction. Two variations were developed with different λ_A-λ_B-combinations. The *1-dim actuator I* was coated at $\lambda_B = 6$, and activated at $\lambda_A = 3$. It is 150mm long and 35mm wide with an active area of $130 * 25mm^2$. The *1-dim actuator II* was coated at $\lambda_B = 6$, and activated at $\lambda_A = 4$. The actuators measure 150mm length and 35mm width with an active area of $130*25mm^2$.

Figure 2 shows the schematic of the pre-stretching process. Figure 3 shows the final actuator and the measurement set-up. To be able to make the measurements, the actuators



(a) Original acrylic film (b) Pre-stretching by $\lambda = \lambda_B$

(c) Coating by $\lambda = \lambda_B$ (d) Relax to $\lambda = \lambda_A$, ready for activation

Figure 2: Schematic of the pre-stretching process

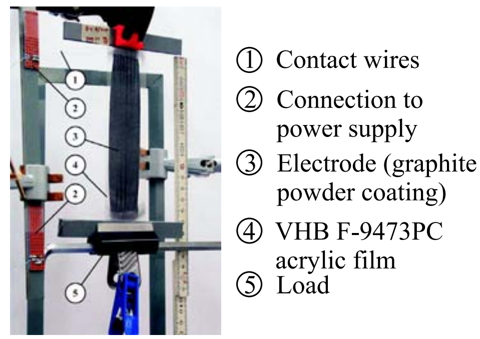


Figure 3: One-dimensionally pre-stretched flat polymer actuator

were attached to a frame with a weight at the lower end to keep the pre-stretching factor (λ_A). When activating, the actuators showed a vertical elongation, which was measured with a ruler.

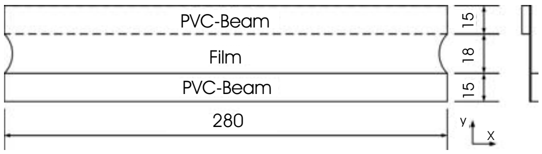
6.3 Two-dimensionally pre-stretched dielectric polymer actuator

The *2-dim actuator* was pre-stretched along the two directions X and Y. The film was coated and activated with the same pre-stretching factors ($\lambda_A = \lambda_B$). The final actuator is 280mm wide and 84mm long with an active area of $260 * 50mm^2$. Figure 4 shows the schematic of a two-dimensionally pre-stretched flat actuator while Figure 5 shows the final actuator and measurement set-up.

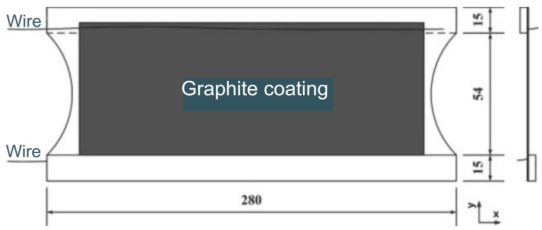
6.4 Cylindric dielectric polymer actuator

The in length direction one-dimensionally pre-stretched polymer, coated with electrodes, was wrapped around a fully compressed spring (see also figure 6). After the film was wrapped around the spring, the spring expanded slightly again, pre-stretching the EAP perpendicularly to its length direction.

When an appropriate voltage is applied, the axial strain of the dielectric polymers allows the compressed spring to expand again. When the voltage is switched off, the dielectric



(a) Schematics of the actuator



(b) Idle state

Figure 4: Schematic of a two-dimensionally pre-stretched flat actuator

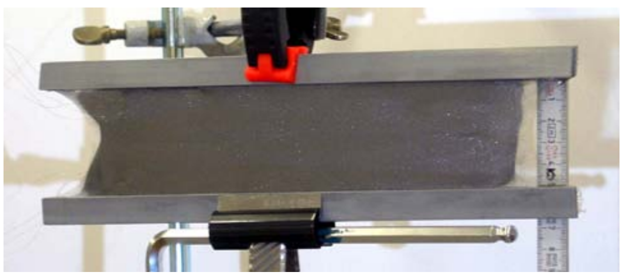
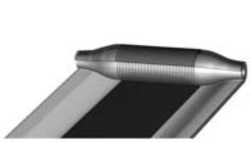


Figure 5: Two-dimensionally pre-stretched flat polymer actuator

(a) Relaxed spring

(b) Compressed spring



(c) Rolled actuator

(d) Idle state

Figure 6: Schematic of cylindric dielectric polymer actuator

polymer contracts and forces the spring back to the neutral state. Thus the output of the actuator is a linear motion with a certain force.

The actuator was assembled and activated by using the pre-stretching factor $\lambda = \lambda_A$. The acrylic polymer was coated with graphite powder with a pre-stretching factor $\lambda = \lambda_B$. Table 8 shows the technical data of the material and Figure 6.4 shows the measurement set-up. The cylindric actuator is $70mm$ long with diameter of $21mm$.

	Original material	Assembly	Activated area
Pre-stretching factor	λ=1	λ_A=4	λ_A=4 (coated with λ_B=8)
Width (mm)	186	93	20
Lenght (mm) (pre-stretching direction)	277	1108	1101

Table 8: Material preparation data

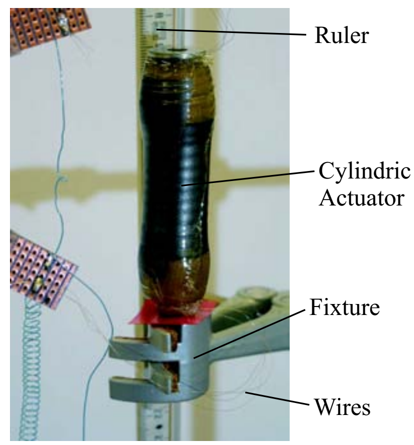


Figure 7: Measurement set-up of the cylindric dielectric polymer actuator

The actuator stays vertically with the lower end fixed to the frame. When a voltage is applied, the actuator shows an axial elongation that can be measured with a ruler.

7. RESULTS

Manufacturing process

The manufacturing process is still a difficult issue, due to the thickness of the material and its elastic and viscous properties. Since the material should change its length when a voltage is applied, it has to be guaranteed that the movement is not hindered by the electrodes, which are needed to apply the electrical field. Thus a major design problem was and is the realization of a flexible electrode. Testing different materials showed, that graphite powder delivers the best results. However, it is necessary that the powder is applied during the pre-stretched condition of the elastomer to avoid cracks and regions without powder in the electrode when the probe expands. A related problem is the particle size and shape of the graphite. If the particles are too large or sharp-edged they may damage the polymer, resulting in shortcuts during actuation.

Since the working principle of EAPs is based on Coulomb forces, the resulting force between the electrodes can be calculated by the following equation:

$$F = \frac{1}{2} \cdot \epsilon_0 \cdot \epsilon_r \cdot E^2 = \frac{1}{2} \cdot \epsilon_0 \cdot \epsilon_r \cdot U^2 \cdot \frac{A}{d^2} \qquad (2)$$

In order to increase the force, the voltage or the electrode size can be increased or the thickness of the polymer itself can be decreased. In order to keep the required voltage as low and the active area as small as possible, the thickness of the polymer has to be reduced by pre-stretching it as much as possible. This process has to be done very slowly and carefully to allow the material to flow and to avoid cracks and damages.

Elongation measurements
Figure 8 shows the elongation rates of the developed actuators compared to the required elongation rate of a haptic feedback device (see Table 2). It is apparent, that the required elongation rate of (10%) was achieved by two actuators. While the *two-dimensionally pre-stretched actuator* even performed 5% more than necessary, the *one-dimensionally pre-stretched actuator I* just reached the requirements. The other *one-dimensionally pre-stretched actuator II* did not reach the requirements. Since both actuators were manufactured under the same conditions (pre-stretching factor $\lambda_B = 6$ for electrode application), the pre-stretching under operation conditions seems to have influence on the maximum elongation. Using $\lambda_A = 3$ showed better results than with $\lambda_A = 4$.

The best results were achieved by the *two-dimensionally pre-stretched actuator*, which was stretched in x- and y-direction by $\lambda_A = 3$.

The *cylindric actuator* with the integrated spring showed a very poor elongation rate and thus seems currently not suitable for the use in haptic feedback devices.

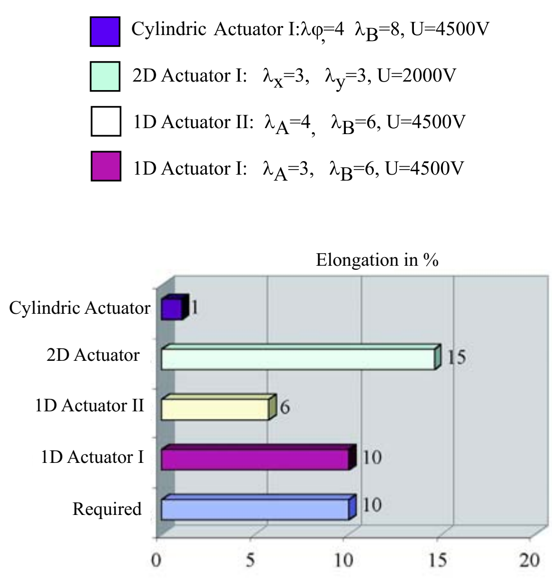


Figure 8: Elongation of the actuators in %

8. FUTURE WORK

Although the results showed the possibility to integrate electroactive polymers into haptic feedback devices, lots of work has still to be carried out. Since the polymer of the flat actuators crept over time, it was difficult to find the right time to actuate and measure their elongation. It is not clear either, how the polymer properties depend on the pre-stretching direction and factors. In order to answer those questions, experiments on material actuation behavior dependent on the pre-stretching factors and time have to be made in future.

The results of the flat and cylindric actuators differ a lot from each other. Simple flat actuators, especially the two-dimensionally pre-stretched ones, show much better actuation capabilities than the cylindric ones. This shows, that the actuation capability is strongly dependent on the actuator's configuration. Therefore, for a successful actuator design, real working conditions for a haptic feedback device have to be taken into account. Although the cylindric actuator shows poor results, it seems to be a good start for a complex EAP actuator design. Optimizations of the configuration, such as the spring constant for instance, should improve the performance.

The boundary conditions and the way planar strains are coupled into one direction seem to be two important key factors as well. In our study, flat actuators were only constrained in one planer direction. The elongations were measured in the length direction. However, deformations perpendicular to it were observed, due to the lack of boundary constraints and coupling structures. Thus, the field induced stress did not contribute to the elongation as desired.

The electrode design is also an important factor. In order to have a high graphite powder density, the polymer was coated at higher pre-stretching factors. To have a better actuation performance we also tried to increase the electrode area. However, using the whole polymer surface as an electrode results in problems when realizing multiple layers. Thus, the layout of the electrodes on the polymer film and the conductive materials itself have to be optimized.

The connectors on the electrodes have to be designed by considering high voltages design aspects. Sharp geometry of wires and connectors may locally increase the electric field and lead to hot spots.

Isolation issues must be considered as well, due to the high voltages required by the electroactive polymers (2-5kV). This can be achieved by keeping the actuation current in a safe range for human beings.

In this study, we didn't consider force and response time, which are also key requirements for haptic feedback devices. The actuation force of EAP actuators will be measured and considered in later actuator designs.

In the papers [13] and [14], actuator design issues were discussed systematically, demonstrating diverse EAP actuators and giving a good overview to potential EAP applications. Whereas the work presented in this paper is a preliminary study in the exploration of EAP-based technologies for haptic interfaces.

9. CONCLUSION

In this study, efforts were done to develop advanced actuation technologies for haptic feedback devices. After going through all possible physical principles and available technologies, the decision was taken to use electroactive polymers due to their promising capabilities. Three flat actuators and one cylindric actuator were developed and tested.

Despite the manufacturing problems and questions regarding the concept design, the flat actuators have proved the inherent actuation capabilities of electroactive polymers. Therefore, electroactive polymers have a great potential to be the future actuators for haptic feedback devices.

10. ACKNOWLEDGMENTS

This work was performed at and supported by the Research Center of EAP Devices in Switzerland, Lab 121, at Swiss Federal Laboratories for Materials Testing and Research. The project is founded by the Swiss National Science Foundation.

11. ADDITIONAL AUTHORS

Additional authors:
Gabor Kovacs, email: gabor.kovacs@empa.ch and
Silvain Michel, email: silvain.michel@empa.ch,
both at the Research Center of EAP Devices in Switzerland, Lab 121, at Swiss Federal Laboratories for Materials Testing and Research (EMPA - www.empa.ch).

12. REFERENCES

[1] Grigore C. Burdea: Force and touch feedback for virtual reality, 1996, ISBN 0-471-02141-5

[2] R. Tao: Electrorheological Fluids: Mechanisms, properties, structrue, technology and applications, 15-16 October 1991, ISBN 981-02-0902-9

[3] R. Tao, R.D. Roy: Electrorheological Fluids: Mechanisms, properties, technology and applications, 20-23 July 1993, ISBN 981-02-1639-4

[4] Kandel Eric R., James H. Schwartz, Thomas M.Jessell; Principles of neural science, 1991, ISBN 0-444-01562-0

[5] Yoseph Bar-Cohen; Electroactive Polymer (EAP) Actuators as Artificial Muscles; Reality, Potential, and Challenges. 2001, ISBN 0-8194-4054-X

[6] A.V. Srinivasan; D. Michael McFarland: Smart Structures - Analysis and Design 2001, ISBN 0-521-65026-7

[7] Yoseph Bar-Cohen; Nanotechnology Using Electroactive Polymers as Artificial Muscles, MSTnews, International Newsletter on Microsystems and MEMS, Germany, Vol. 3/01 (June 2001), pp. 45-46

[8] Chang Liu; Scaling Laws of Microactuators and Potential Applications of Electroactive Polymers in MEMS, Proceedings of SPIE's 6th Annual International Symposium on Smart Structures and Materials, 1-5 March, 1999, Newport Beach, CA. Paper No. 3669-33

[9] EAMEX Japan; 5th SPIE Conference - EAP Actuators & Devices, March 3-6, 2003, San Diego, California, USA

[10] Yoseph Bar-Cohen; Biologically Inspired Intelligent Robots Using Artificial Muscles, 2003 International Conference on MEMS, NANO, and Smart Systems, Banff, Alberta, Canada, 20 Jul 2003 - 23 Jul 2003

[11] WWW.3M.COM

[12] Guggi Kofod; Dielectric elastomer actuator Masters thesis, The Technical University of Denmark, 2001.

[13] Kornbluh Roy, Perlrin Ron, Qibing Pei; Ultrahigh Strain Response of Field-Actuated Elastomeric Polymers, Procedings of the sPIE Smart Materials, 2000

[14] Kornbluh Roy, Pelrine Ron, Qibing Pei Electroelastomers: Applications of Dielectric Elastomer Transducers for Actuation, Genearation and Smart Structures SRI International