Dielectric Elastomer Actuators for A Portable Force Feedback Device

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Abstract. This paper focuses on the development of novel actuators for a portable force feedback glove for, but not limited to, the simulation of open surgeries. A conceptual design of a chain-like actuator based on electroactive polymers is introduced. One actuator element of this chain was built in order to explore and optimize the actuator manufacturing process. Actuators manufactured with this stable process were characterized through isometric and isotonic measurements. The results show that dielectric elastomer actuators are promising for a portable force feedback device.

1 Introduction

The authors found that among all diverse open surgeries there is one common activity, which is the detection of organs with the hand. Surgeons use the bare hands in 20% of the operation time to expose and feel the organ of destination. Therefore, it is important for medical students to gain experiences in haptic sensations during their quite short education periods.

Nowadays, some simulators have been integrated into visceral surgery simulations. They feed sufficient touch sensations back to the surgeons, helping them to control the robotic endeffectors. Unfortunately, these simulators are only limited to specific tasks affiliated with certain instruments [1]-[4]. A glove-like force feedback device provides a possibility to simulate the detection process with the bare hand. It has either local actuators in the glove [5], or has a cable-driven exoskeleton structure with remote actuators [6]. Both force feedback gloves enable the user to feel rigid virtual objects without weight. However, the in-hand located actuators or the bulky structures over the hand restrict the motions of the surgeon's hands. In order to develop a powerful, light weight and non-obstructive haptic interface, we studied the physical principles that generate forces and new actuation technologies. We have found that the dielectric elastomer technology shows a better overall performance than other technologies [7][8].

Dielectric elastomers, a subgroup of electroactive polymers, change shapes when subjected to a electric field. They have light weight, high strain response (215%, [8]) and a short response time [8]; and they are tailorable to fit different applications. Therefore, dielectric elastomer actuators are attractive for applications including biomimetic, robotic etc [9][11].

In this paper we discuss the development of dielectric elastomer actuators for glove-like force feedback devices. We first describe the requirements on actuators, then a conceptual design of a chain-like actuator and a stable manufacturing process of an actuator element. We then present measurements and results. In the end we conlude and discuss the work.

2 Requirements

In order to compare and select the actuation technologies, and to get the prerequisites to a proper actuator design, it is necessary to understand the haptic-related issues during the detection, as well as the human haptic system [7]. Table 1 summarizes typical characteristics of the human hand required for a surgery simulation (typical values for other tasks are added in brackets).

The actuator has to generate forces with a human perceptual bandwidth when displaying forces to the user's fingertip. When the operator does not touch a virtual object, the actuator should follow a voluntary motion of the finger without impeding this motion. The elongation is taken as a relative length change of a tendon starting from the wrist to the fingertip, when the hand bends from the open position to the fist. Furthermore, Brooks recommends that for a satisfactory performance the control bandwidth has to be at least 10 times the necessary bandwidth [13][14].

Requirements	Surgery haptic simulation (Human haptic system)
Min. sensing pressure	0.2 N/cm^2
Max. force exertions of the fingers	5 N (30-40 N)
Sustained force exertions (15% of the max. force exertions)	0-5 N (4.5-7 N)
Force control bandwidth of the fingers	1-30 Hz
Perceptual bandwidth	10-320 Hz (10-1000 Hz)
Max. elongation	8%

Table 1. Requirements on actuators for force feedback gloves [12]-[15].

3 Conceptual design of an actuator based on dielectric elastomers

3.1 Dielectric elastomers

The working principle of a dielectric polymer actuator is shown in Figure 1. When a high DC voltage (kV) is applied, a thin dielectric elastomer film (μm) sandwiched by compliant electrodes expands in planar directions due to a pressure in the thickness direction induced by an electric field. When the voltage is switched off, the film regains the original shape.

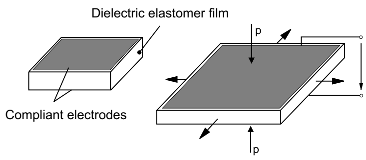

Fig. 1. Working principle of a dielectric elastomer actuator.

Assuming that the volume remains constant, the effective pressure [9] is

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

where ϵ is the relative permittivity of the elastomer, $\epsilon_0 = 8.854 \cdot 10^{-12} As/Vm$ is the permittivity in vacuum, U is the applied voltage and d is the thickness of the elastomer film. The pressure increases quadratically with the electrical field and thus it is the main relationship governing the actuator response.

3.2 Conceptual design of the chain-like actuator

Figure 2. L. shows the schematic of a chain-like actuator for the index finger, which can also be applied to other fingers. The actuator is mounted on a rubber glove. One end of the chain is grounded to the body, a nylon band around the wrist. The other end is attached to a ring around the fingertip. During a voluntary motion of the human operator, the actuator is controlled to follow the motion. As soon as the human operator contacts a virtual object, the actuator is deactivated and tries to contract to its initial shape. Thus, it gives a resistence force via the ring onto the ventral side of the fingertip, blocking the finger's motion.

Figure 2. R. shows a demonstrator of the chain-like actuator. Several actuator elements are connected in series to form a chain. Each actuator element works in principle the same as the aforementioned dielectric elastomer actuator. However, the output is restricted only in the length direction, which contributes to the final output of the chain. An actuator element comprises four parts: a *dielectric elastomer film*, a *fixture* that holds the pre-tension, *compliant electrodes* and *connectors* that feed the actuator.

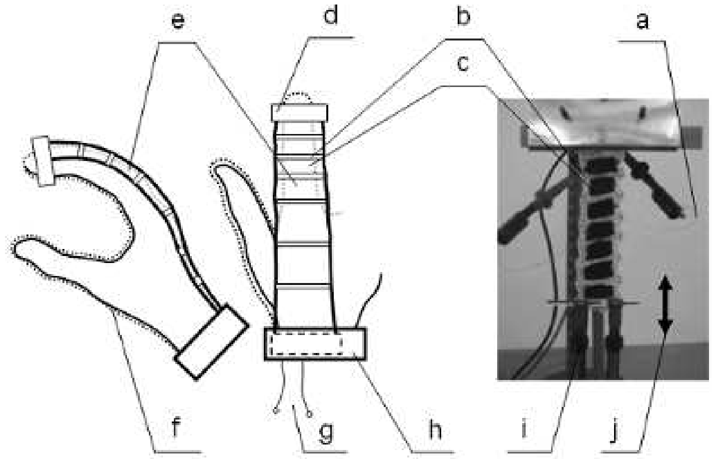

Fig. 2. L.: Schematic of a chain-like actuator for the index finger. R.: Demonstrator. *a*: connector, *b*: fixture, *c*: dielectric elastomer film sandwiched by compliant electrodes, *d*: ring, *e*: chain-like actuator, *f*: rubber glove, *g*: power supply, *h*: nylon band, *i*: mass, *j*: output direction.

4 Actuator manufacturing

The manufacturing process of a one-layer actuator element is briefly introduced in four parts.

Dielectric elastomer film: A commercial available acrylic dielectric elastomer film VHB 4910 [16] was used. It was radially pre-stretched by a torus (Figure 3.1.). The thickness after a two-turn pre-stretching is 0.109 mm, starting from an original thickness of 1 mm.

Compliant electrode: Grease, graphite powder, graphite powder mixed with silicone oil, hammered copper, and beaten gold were tested concerning their thickness, adhesion to the dielectric elastomer film, difficulties in handling, and electrical break down voltage.

In order to prevent the sticky acrylic film from agglutinating, talc was applied onto the the film with the central areas on both sides protected with circular masks (Figure 3.2.). The beaten gold with a thickness of 250 nm was applied to the film when it was one turn more pre-stretched than the actually required pre-stretching. When rewinding this additional turn, a corrugated electrode surface resulted (Figure 3.3-5.).

Connector: Copper tape, metal aluminium tape or aluminium foil were compared concerning their resistance, dimension, and adhesion. The copper tape with an adhesive layer was chosen (Figure 3.6.).

A protective film (Figure 3.7.) of the same elastomer was used to eliminate peak stresses in the transitions from the rigid fixture to the highly pre-stretched film.

Fixture: Two strips of the same elastomer, that stick to the polymer film, hold the pre-tension in the middle of the film. (Figure 3.8.). The upper and the lower end of the film were fixed by plastic films (Figure 3.9.) and were then fixed by the aluminium clamps for the measurement setups. These rigid parts hold the pre-tension on both ends of the film.

Based on this manufacturing process, multi-layer actuators can also be produced by stacking the elastomer films and compliant electrodes.

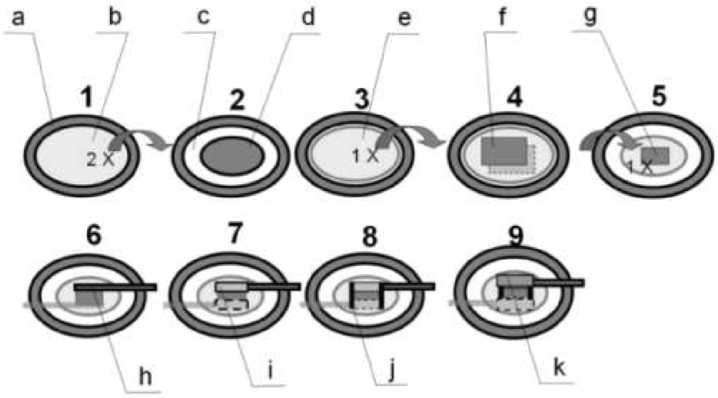

Fig. 3. Manufacturing process of a one-layer actuator element. *a*: torus, *b*: dielectric elastomer film, *c*: talc, *d*: circular mask, *e*: dielectric elastomer film, *f*: electrode, *g*: compliant electrode, *h*: connector, *i*: protective film, *j*: strips, *k*: plastic film.

5 Measurements

Isometric and *isotonic* measurements were carried out to characterize the maximum strain and the maximum contractile force of the actuator. The *isometric* measurement gives the contractile force versus the voltage while the actuator's length remains the same. The *isotonic* measurement determines the relative change of the actuator's length versus the voltage under a constant load.

Isometric measurement: Figure 4. L. shows the setup for the isometric measurement. Both ends of the actuator were fixed by two aluminium clamps with the upper clamp connected to a force transducer S2 by HBM. The signals were amplified by a measuring amplifier (AE 301 S7, HBM). The driving voltage (square wave signal) was provided by a regulated high voltage power supply (AIP HCL 35-12500POS, F.u.G. Elektronik GmbH) and was controlled manually through a high voltage relay (H-507-1004, Hengstler). The applied voltage on the actuator was measured by using a high voltage probe by Peaktech. The signals from the force and voltage measurements were acquired by a data acquisition card (NI PCI-6070E, National Instruments) and Labview (BNC-2090) using two channels.

A defined initial load was applied to the actuator by adjusting the distance between the two clamps. The length was kept constant during all measurements. When the actuator was activated, it relaxed and lowered the pre-tension. The force difference was measured as the maximum contractile force.

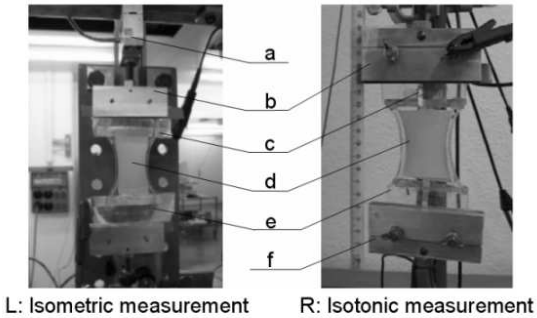

Fig. 4. Setup of the *isometric* (L.) and *isotonic* (R.) measurement. *a*: force transducer, *b*: aluminium clamps, *c*: connectors, *d*: dielectric elastomer applied with compliant electrodes, *e*: plastic film, *f*: mass.

Isotonic measurement: Figure 4. R. shows the isotonic measurement setup. The actuator was fixed at the upper end to an aluminium clamp and at the lower end to a mass to keep the initial pre-tension. A video extensometer (OVEX ME-46) was used to measure the elongation of the actuator under a defined mass. The data aquisition channels, high voltage supply, relay and probe were the same as for the isometric measurement.

6 Results

Linear actuators with one-layer and multi-layers were manufactured and characterized. Results of the one-layer linear actuator are presented.

Isometric measurement (Figure 5. L.): The contractile force versus the voltage was measured when the actuator was subjected to different initial pre-strain forces. The results show that the contractile force increased non-linearly when the voltage or the initial force increased. A force variation of 0.7 N was measured at 4.5 kV under a initial pre-strain force of 4 N. All forces were acquired 0.2 *seconds* after the voltage was applied.

Isotonic measurement (Figure 5. R.): The elongation versus the voltage was measured when the actuator was subjected to different masses. The results show that the elongation increased with the voltage approximately in a quadratic manner. The larger the mass was, the larger the elongation became. An elongation of 10.2% was measured at 4.5 kV under a mass of 230 g. All elongations were acquired 4 *seconds* after the voltage was applied, since they tended to be stable then.

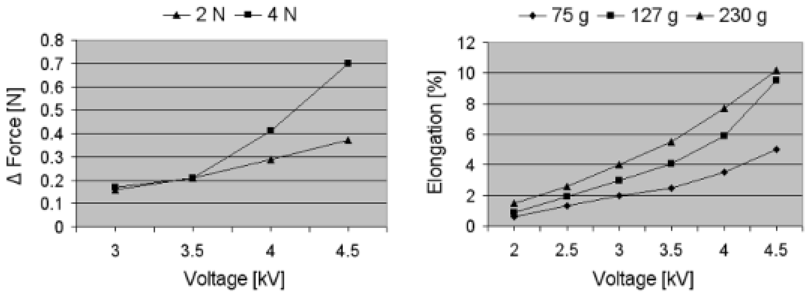

Fig. 5. L. *Isometric measurement*: The variation of contractile forces vs. the voltage under the initial forces of 2 and 4 N. R. *Isotonic measurement*: the elongation vs. the voltage under the masses of 75, 127 and 230 g.

7 Conclusion and Discussion

In this study, the concept of a chain-like actuator based on the dielectric elastomer technology is presented. A stable manufacturing process for the one-layer actuator element was found. The results of the isometric and isotonic measurements indicate that, concerning the light weight, contractile force, and the elongation, the dielectric elastomer actuator of a compact structure promises to provide the required force feedback to the user. Variations in the actuator design such as multi-layer, multi-element or multi-layer-element configurations might enhance the actuator performance, and allow other haptic display tasks in virtual environments.

The experiments with two samples for each measurement are neither able to provide statistical results, nor to determine key parameters for the actuator configuration. Actuator characterizations (including dynamic responses) based on the established manufacturing process will be done in future.

The required electrical field (10-100 $V/\mu m$) is much higher than the break down strength of air (2-3 $V/\mu m$)). The actuator needs to be sealed and insulated from air. In addition, the electrical insulation and the over-current protection in the electric circuit have to be well studied in order to provide sufficient electrical safety to the user.

The inherent viscosity of the acrylic elastomer resulted in the relaxation during isometric measurements and in the creeping during isotonic measurements. These time-dependent and non-linear responses are great challenges for the actuator control. The high pre-stretching, although reducing the viscosity, makes the support system and manufacturing more complex. Silicone elastomers with much less viscosity might be an alternative material.

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