Soft wearable non-vibratory tactile displays

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***Abstract*— This paper presents a new type of wearable finger-tip tactile displays aimed at providing electrically tuneable tactile stimuli interactions with soft bodies. This is achieved by a new actuation technology based on soft electroactive polymers, capable of generating large and quasi-static displacements at moderate forces. This is intentionally different from the high-frequency small vibrations at high forces that are used in several state-of-the-art tactile displays. We describe the ongoing development of devices having a volume of 20x12x23 mm and weigh of only 6 g on finger, which can render electrically tuneable displacements of up to 3.5 mm and forces of up to 0.8 N.**

I. Introduction

Wearable tactile displays able to mimic interactions with soft bodies are required in a number of emerging fields, such as virtual environments where users could touch and manipulate computer generated deformable objects. Examples of possible applications include training for medical operators, teleoperation, computer aided design and 3D model exploration. Such tasks might take advantage of human-machine interfaces able to realistically mimic the tactile feeling produced by the contact with a soft object.

Rendering soft bodies with a large compliance requires an actuation technology capable of generating large and quasi-static displacements at moderate forces. Those properties contrapose to the high-frequency small vibrations at high forces that are typically used in several state-of-the-art tactile displays. So, it should be not surprising that tactile feedback is still underutilised in wearable devices, especially for virtual- or augmented-reality systems aimed at mimicking realistic interactions with soft bodies.

The fact that the greatest majority of approaches today is based on the use of vibrational haptic feedback is likely due to a technological problem: a lack of adequate actuation solutions to generate large and quasi-static displacements at moderate forces via compact, lightweight, silent and energy efficient technologies, Indeed, so far there have been a number of attempts to create wearable, fingertip-mounted tactile devices (for an overview, see [1]). For example, servo motors mounted on fingers have been used to move a plate with up to three degrees of freedom [2]-[3]. Another common technique is based on the use of compact vibratory motors placed upon individual fingertips, typically through a gloved interface [4]-[6]. Other devices are frequently driven by pneumatic actuation, where a deformable cavity is inflated and deflated to apply dynamic pressures [7]-[10]. Although these solutions have been demonstrated to be adequate to render tactile sensations, they appear to be burdened by their underlying actuation technology, in terms of size/weight, realism of sensation and portability.

Aimed at overcoming such limitations of conventional approaches, in this work we used the soft actuation technology described below.

A. *Dielectric Elastomer Actuators for Tactile Devices*

Dielectric Elastomer Actuators (DEA's) are an emerging smart material-based electromechanical transduction technology [11]-[13]. They are part of the broader family of materials known as electromechanically active polymers [14]. The most basic DEA configuration consists of a layer of an elastomeric dielectric material with compliant electrodes applied to opposing surfaces. When an electric field is applied across the dielectric material, the resulting electrostatic stress causes a compression perpendicular to the electrode plane, and an expansion in the parallel plane. Due to the high electric fields needed to drive DEA devices (~10-100 V/μm), the typical voltages required are within the kiloVolt range, although at low currents [12]. DEA's are typically characterised by large electrical strains, fast, stable and silent operation, compact size, low weight, shock tolerance, low power consumption and no overheating [11]-[13],[15].

To date, there have been a number of reports on haptic devices exploring the use of DEA's. Koo et al. developed a wearable device placed upon the fingertips, which consisted of a 10x10 array of individually controllable bucking dots [16]. Koop and Rossiter focused on providing latero-tactile stimulation of localised areas of skin [17]. Zhang et al. developed a haptic device consisting of a roll of a DEA membrane placed between the thumb and forefinger [18].

Our approach focuses on a DEA membrane coupled to a passive touchable membrane through an insulating fluid. This technology, which is referred to as hydrostatically coupled (HC)-DEA's [19], was used in this work and is presented below.

B. *Hydrostatically Coupled-DEA's for Tactile Displays*

The schematic structure of an HC-DEA used to provide tactile stimuli to the finger pad is presented in Figure 1.

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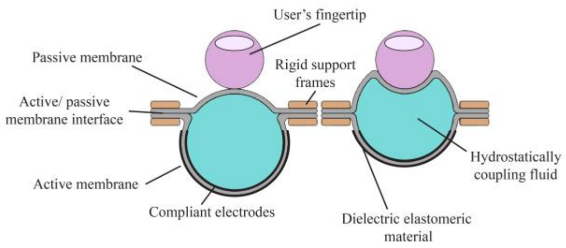

Figure 1. Schematic illustration of a basic HC-DEA tactile display with voltage on (left) and voltage off (right).

In their implementation for tactile displays, HC-DEA's provide an electrically safe configuration to apply tuneable forces to fingertips, through a soft bubble interface. This concept was previously demonstrated by our group to stimulate a single finger in a non-vibratory mode [20]. It basically consists in a fluid mediated transmission of actuation between an active membrane and a passive membrane, which works as the end effector (Figure 1).

Whilst it was demonstrated to be effective, the adopted design was too large to be considered for a multi-finger system. So, further to that work, recently we presented an improved design suitable for multi-finger operations, based upon an improved HC-DEA multilayer structure, which could generate forces up to 0.6 N with a volume of 30x18x24 mm [21]. Through further investigation, that new design was still found to be too large and cumbersome, and proved difficult to integrate with an off-the-shelf low cost hand tracking sensor, without modification of the software component. Indeed, we considered it important to be able to use our wearable tactile devices alongside existing hand tracking sensors, so as to reduce the complexity of development of affordable virtual- or augmented-reality systems.

Moving from those findings, this paper presents a new design, which allowed us to obtain the following achievements: 1) reducing the device size, so as to create a multi-finger system; 2) enabling the integration with a low cost hand tracking commercial sensor, so as to achieve a fully functional system for virtual- or augmented-reality applications.

II. Tactile Display Design and Fabrication

A. Actuator Design

A drawing of the proposed display is shown in Figure 2. The HC-DEA had a base diameter of 12.5 mm and a height of 11 mm. The lateral size was empirically selected as a (non-optimised) trade-off between the need for maximising the contact area with the fingertip (so as to maximise the perceivable force) and the need for minimising the overall encumbrance of the device.

The actuator's active membrane had a multi-layer structure, consisting of three dielectric elastomer layers intertwined to compliant electrode layers. The combination of multiple layers formed a stack (mechanical series) of DE capacitors, which were electrically connected in parallel. This enabled the active membrane to be thicker, thereby ensuring a higher blocking force with respect to a single layer, without increasing the driving voltage.

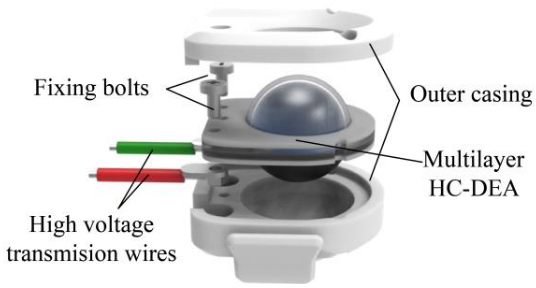

Figure 2. HC-DEA tactile display with its outer casing and the high voltage supply wires.

To obtain that structure, three pre-stretched elastomeric membranes were stacked on top of each other with compliant electrodes being created between adjacent layers, as described below.

B. Actuator Constitutive Materials

The active and passive membranes consisted of an acrylic elastomer film (VHB 4910, 3M, USA). The films were bi-axially pre-strained by 350%, prior to conferring them into a dome-like shape while manufacturing the HC-DEA. Although higher pre-strains have been demonstrated to be optimal for VHB-based DEA devices working in planar mode [22], we had to limit the pre-strain in consideration of the non-planar configuration assumed by the membranes in our device. Indeed, for higher pre-strains, the active membranes could become more prone to electrical breakdown and mechanical fracture, as a result of excessive thinning, due to three factors: 1) their dome-like shaping during manufacturing; 2) their further passive stretching, caused by the user while wearing the device; 3) their further active stretching, caused by the applied electric field while activating the device. Empirically, we found that 350% was an adequately safe pre-strain amount, although it was not optimized (thereby leaving room for possible performance improvements in the future).

Compliant electrodes were applied on both sides of each active membrane using an airbrush. The electrode material consisted of a carbon black powder (Black pearl 2000, Cabot, USA), which was mixed with an uncured silicone pre-polymer. After the deposition, the mixture was cured at room temperature for 10 mins. The resulting compliant electrodes had an average sheet resistance of 45 kΩ/sq, as measured according to the procedure described by the standards for DE transducers [23].

C. Actuator Manufacturing

The HC-DEA was coupled to two rigid support frames fabricated from 0.5 mm laser-cut acrylic sheets. These were carefully designed to be as compact as possible. Each frame was made 2.5 mm larger in radius than the bubble, so as to leave a sufficient annular area for adequate bonding among the membranes.

The actuator was assembled as follows. The pre-stretched passive membrane was placed over an empty chamber having a circular hole of the same size of each compliant electrode. Vacuum was applied in order to deform the membrane and to create a cavity that was then filled in with 0.8 ml of an insulating silicone grease (8462, M.G. Chemicals, Canada).

The electrode-coated membranes were manually stacked and then coupled to the other membrane. The adhesiveness of the VHB film allowed for proper bonding. After 10 minutes the membranes were removed from the vacuum chamber, and bonded to a stiff plastic frame. The resulting final shape of each membrane was a spherical cap having a height of 5.5 mm and a base radius of 12.5 mm. The frames were designed to integrate fixing bolts (Figure 2), which penetrated the electrodes, offering a robust and safe method to secure the electrodes to the high voltage wires, as well as the whole actuator to its external casing (detailed in the following).

The actuator was integrated within a plastic outer casing designed to be placed upon the fingertip, allowing the finger pulp to be in contact with the passive membrane. The casing was designed to meet the following requirements: 1) protect the user from the high voltage components of the actuator; 2) be as compact and light as possible in order not to burden the user; 3) secure the device to the user's fingertip comfortably; 4) enable the use of an off-the-shelf optical hand tracking sensor, whose detection accuracy should not be worsened by the optical reflecting properties of the display, as specified below.

The last requirement listed above challenged the design of the casing in terms of shape, size and surface properties. Indeed, according to the principle of operation of the adopted optical sensor (stereo image comparison of an infrared illuminated scene) the casing required an optical signature not too dissimilar from that of the finger pulps. In other words, a finger covered by the display had to be detected by the system as if it was a naked finger. The best tracking results were achieved by using materials having a semi translucent or light colour, without a gloss finish. The final casing was produced by a 3D printing process, using a translucent resin (VeroClear-RGD810, Stratasys, USA). The casing had a small encumbrance, as shown in Figure 3.

Figure 3. Dimensions (mm) of the tactile display (excluding the elastic fixing strap).

To attach the casing to the user's fingertip, an elastic strap with a thickness of 1.5 mm was produced using a transparent silicone elastomer. The transparent elastic strap allowed the device to be secured to the fingertip easily, without precluding optical tracking. A picture of the tactile display is presented in Figure 4.

The weight of the fingertip-mounted display (including the fixing strap) was 6 g.

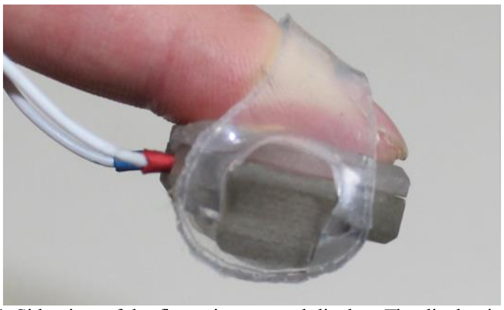

Figure 4. Side view of the fingertip mounted display. The display is secured to the fingertip by means of a silicone strap.

D. *Control Electronics*

As mentioned previously, DEAs typically have to be driven with high voltages, within the kV range (owing to the typical usage of thick and inefficient elastomer films). In previous designs presented by our group, the voltage was applied via a low-to-high voltage DC-DC converter placed within a rigid casing at the tip of the user's finger [20]. Although this allowed for locating all the high voltage parts of the system at a single place, as well as using more flexible low voltage transmission cables, it made the wearable device cumbersome and unsuitable for multiple fingertip usage.

To overcome this drawback, in this work a DC-DC converter (EMCO Q50, EMCO High Voltage, USA) was arranged (one for each display used) in a desktop control box. Each converter was fed with a 0.7-4.0 V signal to generate a voltage up to 4 kV, as required to drive the actuator. It is worth noting that the minimum input voltage was 0.7 V, as this is the lower limit of the range of approximate linearity exhibited by the converter. The high voltage driving signal was transmitted to the fingertip-mounted device through a flexible coaxial cable. In order to enable a control of multiple displays independently, we used two 8-bit Pulse Width Modulated (PWM) output channels of a low cost micro-controller (Arduino Micro, Arduino, Italy). The PWM signal (having a cycle frequency of 490 Hz) was smoothed with a low pass filter (made of a 4.7 μF capacitor and a 150 Ω resistor), which enabled almost linear control of the high voltage driving signal. Due to the high current demands of multiple low-to-high voltage DC converters, we used an operational amplifier (TCA0372, ON Semiconductor, USA) powered by an external regulated 5V-1A, power supply. A Schottky diode was placed in series to the converter's input, so as to avoid back voltages. Moreover, a high-voltage discharge resistor of 200 MΩ was arranged in parallel to the output of each converter, in order to both let it work with proper electrical loading and allow the actuator to be quickly discharged.

III. Electro-mechanical Characterisation

A. *Test Specimens*

The electromechanical performance of the display in terms of achievable force and displacement was assessed as described below, on three specimens.

B. *Voltage-induced Force*

To determine the force output as a function of the applied voltage, blocking force with constant deformation tests were performed with a dynamometer (3300 single column, Instron, USA), equipped with a 10 N load cell (2519-10N, Instron, USA), in conjunction with a circular 12 mm diameter flat faced indenter (which was used so as to align with previous methodologies employed by our group). At the start of each test, the actuator was deformed through the application of a voltage of 4 kV, which was controlled by the electronics described in the previous section. The voltage caused the actuator's passive membrane to move down until it was almost flat and aligned with the top rigid support frame. The indenter was then lowered onto the deformed passive membrane until a contact was established. The latter was defined as the situation corresponding to an offset force of 0.05 N (value empirically chosen according to the sensitivity of the load cell). Once this offset value was reached, the voltage across the actuator was dropped from 4 to 0.7 kV over a 10 second period. Force data were collected at a rate of 100 Hz. The force samples for each voltage step were then averaged to produce a single force value corresponding to that step. The test was repeated 5 times for each sample. Results are presented in Figure 5.

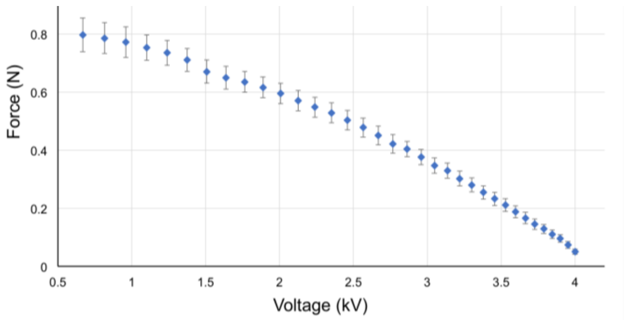

Figure 5. Force-voltage performance of the tactile display. Error bars represent the 95% confidence interval.

C. Voltage-induced Displacement

To measure the passive membrane's displacement, we used a laser measurement device (optoNCDT ILD 1402-5, Micro-epsilon, UK). For this test, the measurements were taken as the voltage across the actuator was increased from 0.7 kV to 4 kV over a 10 second period. Displacement data were averaged to produce a single displacement value for that step. Results are presented in Figure 6.

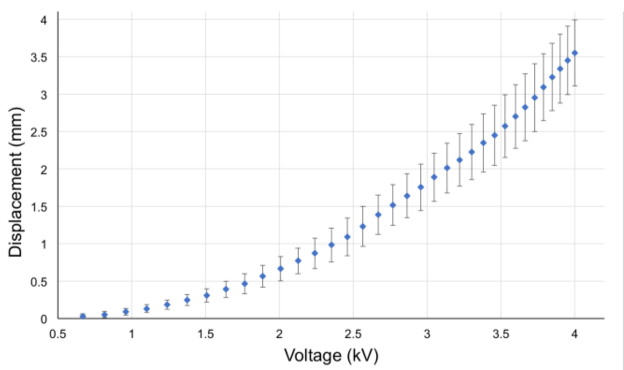

Figure 6. Displacement-voltage performance of the tactile display. Error bars represent the 95% confidence interval.

IV. Use of the Display in Combination with an Optical Hand Tracking Sensor

Two fingers (thumb and index finger) of one hand of a volunteer were equipped with two tactile displays. The spatial position and orientation of each segment of each finger was continuously detected via a low cost commercial optical sensor, called LEAP Motion hand tracking system [24]. It uses stereo infrared cameras to track motions, without markers. Several other optical systems are available for 3D fingertip tracking, such as the Kinect (Microsoft, USA) and the Duo MLX (Code laboratories, USA). We opted for LEAP Motion as we focused on interactions with virtual objects/scenes at a desktop scale, where that system competitively offers high accuracy at a low cost. However, for dynamic scenarios, inconsistent and unreliable values were obtained, especially for tracking of objects at the periphery of the LEAP Motion field of view [25],[26]. So, in this work, we limited the use of the system to interactions within a workspace volume of 200x200x200 mm^3, which allowed for accurate tracking.

A custom control program running on an external desktop computer was developed to perform the following tasks: continuously track the position of the fingertips wearing the tactile displays, detect collisions of represented virtual fingers with virtual objects, and generate appropriate tactile and graphical responses, respectively on the fingers and on a computer screen in front of the user. The interfacing with the LEAP Motion tracking device was achieved using the software LEAP motion SDK, version 2.3.1. A graphical user interface was programmed using Java version 8.0 language.

The tactile response data were sent from the computer through a wired USB connection to a PWM output pin of the external micro-controller described above. The whole experiment setup is shown in Figure 7.

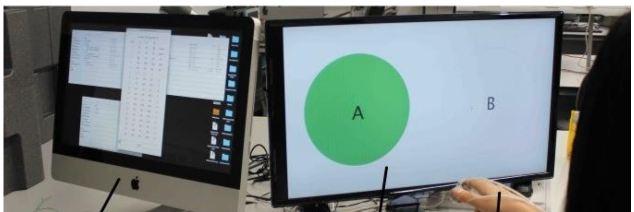

Figure 7. Experimental setup to test the tactile display: processing computer (A), high voltage control unit (B), visualisation screen (C), LEAP Motion hand tracking sensor (D) and two tactile displays placed on the user's thumb and index finger (E).

An assessment of the psychophysical performance of the new proposed display using this system for various tactile tasks is currently ongoing and will be reported in future publications.

V. Discussion

A. High Voltages: Implications on Safety, Size and Cost

The main limitation of this tactile display technology is the need for high driving voltages (a few kV for the current prototypes), which has the implications discussed below.

In terms of electrical safety, dealing with such high voltages is clearly not desirable. However, this drawback is mitigated not only by the actuator's unique design (separation between the fingertip and the high voltage membrane via a large insulating chamber), but, especially, by the fact that there's no need for a high driving power (as the electrical load is capacitive), which allows for using electrically safe sources. Indeed, the maximum power of the DC-DC voltage converter used in this work was 0.5 W.

The low power requirement favours the adoption of relatively compact high voltage components. For instance, the DC-DC converter that we used was a 13 mm sided cube. However, this size is still excessive if the aim is to have electronics that is both multi-channel (to stimulate multiple fingers independently) and wearable. For instance, this would be the case if all the five fingertips of a hand had to be equipped with tactile displays, wirelessly driven by a battery powered control unit mounted on the back of the hand, i.e. an extension of the single-finger Bluetooth-controlled system that we demonstrated previously [20]. To address this need for further miniaturisation, one strategy could be to implement multiplexed driving signals, through high voltage transistors, from a single high voltage source.

Nevertheless, regardless of the control strategy used, any high voltage electronics will always be bulkier (due to the need for insulations) and more expensive (also due to a lower market share) than any electronics generating voltages one order of magnitude lower. So, for a major breakthrough, a reduction of the driving voltage to a few hundred Volts is imperative. This need can be addressed as described below.

B. Strategies to Reduce the Voltage

Lowering the driving voltage should target about 200 V, which is typical for the low-cost and low-size electronics of common piezoelectric actuators. To reach that goal, there are two strategies: i) at a material development level, the approach is to synthesize elastomers with a higher dielectric constant [27],[28]; ii) at a material processing level, the approach is to create membranes with a lower thickness. To meet those needs, the best materials of choice (in several respects, including reliability, versatility and cost) today are silicone elastomers. Even with off-the-shelf compositions, preliminary studies have shown the possibility of reducing the thickness to a few microns while preserving actuation capability [29]. Such evidence makes it more realistic that the DEA technology might soon use the compact and cost-effective electronics originally developed for piezoelectric transducers.

Nevertheless, such a technological trend towards films with lower thickness implies the need for stacking more layers to preserve the elastic force of the resulting membranes. So, multi-layer manufacturing processes will have a growing importance in the future.

C. Strategy to Limit Viscoelastic Losses

The envisaged use of silicone elastomers in the future will also address a limitation that characterises the particular material used in this work, i.e. the VHB poly-acrylic elastomer film by 3M. This is one of the most studied soft insulators for DEA's [11]-[13], as it facilitates prototype fabrication and is capable of large electromechanical strains and stresses. However, it also has a well-known poor viscoelastic performance that causes significant creep and stress relaxation [30]. We presented a characterisation of the stress relaxation of an early prototype of our displays in a previous paper [20].

As silicones typically have lower viscosity, they lead to DEA devices that are more stable and have faster response [31]. Nevertheless, so far in general DEAs made of off-the-shelf silicones have shown, as compared to VHB-based devices, lower electromechanical strains and stresses, mainly due to the lack of combination of a low elastic modulus with a high dielectric strength. This means that, as long as improved silicone formulations are not demonstrated, there will be this trade-off between electromechanical and viscoelastic performance.

VI. Conclusions and Future Work

This work described new compact tactile displays, aimed at providing non-vibratory stimuli to fingertips to simulate tactile interactions with soft virtual bodies.

Forces up to 0.8 N and displacements up to 3.5 mm could be generated with a 6 g device, whose small size and rounded shape allowed it to be worn on individual fingertips without precluding an optical tracking of them.

We also showed that this tactile display can be used in combination with an unmodified low-cost and compact hand tracking sensor.

These achievements make possible future implementations of simpler, more portable and more cost-effective virtual reality (VR) or augmented reality (AR) systems to mimic tactile interactions with virtual soft bodies. We are currently working towards that goal.

Acknowledgements

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