

A dielectric elastomer actuator-based tactile display for multiple fingertip interaction with virtual soft bodies

Hugh Boys^{1,2}, Gabriele Frediani², Stefan Poslad¹, James Busfield², Federico Carpi³

¹ Queen Mary University of London, School of Electronic Engineering and Computer Science, London, UK,

² Queen Mary University of London, School of Engineering & Materials Science, London, UK

³ University of Florence, Department of Industrial Engineering, Florence, Italy

ABSTRACT

This paper presents a novel wearable tactile haptic display for rendering soft body sensations to multiple fingertips with electroactive smart elastomers. The system uses newly developed multi-layered hydrostatically coupled dielectric elastomer actuators (DEAs), which have been designed to apply a localised tunable force to a user's fingertip via a soft electrically-deformable interface. The system is comprised of DEAs which are fingertip mounted and are driven individually by a wired connection to a control unit. The force applied to the user's fingertip is based on the user's fingertip position which is monitored by an optical three dimensional finger tracking system. This novel tactile display system is conceived to convey soft body interactions within virtual environments. To demonstrate this, a simulator capable of demonstrating virtual objects of varying tactile haptic properties has been developed. This paper presents preliminary results of ongoing testing, as well as data pertaining to the characterization of the device in terms of force response. The paper also outlines the current limitations of the proposed technology and challenges to be addressed for further developments.

Keywords: Tactile Display, Dielectric Elastomer Actuator, Wearable, Haptics, Human computer Interface, Soft, Virtual.

Acknowledgement: This paper has been partly funded by EPSRC and AHRC Centre for Doctoral Training in Media and Arts Technology (EP/L01632X/1)

1. INTRODUCTION

Current types of human computer interfaces are limited in haptic/tactile expression, especially when compared to the rich and vibrant interactions that can be generated using the visual and acoustic sensory. Although it is possible to interact with virtual and augmented reality environments via your hands, using optical tracking devices such as the Leap motion [1] and Microsoft kinect [2], there are still limited options when it comes to generating haptic/tactile feedback sensations based upon the interactions of our hands within these environments as is briefly reported below.

Background and related work

Historically there have been a number of attempts to generate haptic feedback sensations within virtual environments, but they have typically been in the realm of kinaesthetic devices, restricting the natural movement of the user through a fixed point desktop mounted actuating arm or an exoskeletal frame. Examples of this approach can be seen [3]–[7]. The main issues concerning such haptic devices are represented by a large size, weight, energy consumption and acoustic noise, which limit portability and comfort. This is due to the actuation technologies employed, which are primarily stepper motors and linear actuators. Moreover, due to the mechanical linkage nature of these types of devices, additional limitations arise from a restriction of their natural movement and a limited working area.

An important avenue of haptics is represented by tactile displays, which are devices that focus on the generation of mechanical stimuli that can be perceived at the level of the skin. There have been a number of commercially-developed devices for this purpose, but typically they have focused on delivering vibrotactile sensations through vibrational actuators [8]–[11]. This could possibly be attributed to the prevalence, size and relative ease of control of vibrational actuators.

A perhaps more natural and expressively useful tactile sensation to render is represented, in our view, by a localised tuneable mechanical pressure applied to the fingertips through a soft interface. Systems for such a purpose have been

developed with pneumatic and hydraulic technologies, which have been demonstrated to be useful in medical training scenarios [12]–[14]. Especially, for the simulation of soft body palpation (a common practice employed by physicians to access organ health through the tactile responses of an organ), the common approach is to use pneumatically or hydraulically inflated elastomeric cavities. Although pneumatic actuation can produce high ranges of force, it is reliant on relatively large systems that need pumps, valves and regulators. This makes miniaturisation more complex, thus limiting the adoption of the technology for wearable based tactile systems.

An emerging actuation technology that has potential to address a significant number of issues for wearable tactile rendering devices is represented by dielectric elastomer actuators (DEAs). These are insulating elastomeric materials that can be deformed by the application of voltage. The voltage is applied across the elastomeric dielectric material through opposing compliant electrodes. This creates a compressive stress between the opposing electrode surfaces, causing both a compression along the direction of the applied electric field and an expansion in the plane perpendicular to it [15]–[18].

So far, there have been few approaches to use the DEA technology for tactile haptic interfaces. Koo et al [19] have presented a wearable design comprised of a ten by ten array of individually controllable actuating dots. These dots moved up and down, to apply to different regions of the user's fingertip, localised tunable forces of about 14 mN at 3.5 kV. Another approach has been in a device conceived to exert a uniaxial mechanical force between the thumb and three other fingertips of the same hand; although this device boasts forces of up to 7 N with actuating Voltages between 0 to 3.5 kV, the device appears cumbersome and constricts natural free movement of the user's hand [20]. A laterotactile device has been developed to provide lateral shear stimulation of the fingertip through four rigid pins which are placed upon the surface of the skin. These pins, actuated by a dielectric elastomer membrane, provide compressive and tensile forces upon the fingertip skin. Although this device has scope for miniaturization and provides adequate separation between the high voltage membranes and the users fingertip, stimulation is limited to laterotactile sensations [21].

Recently, the stimulation of individual fingertips through a fingertip-mounted soft surface interface hydrostatically coupled through a non-compressive gel to a DEA membrane has been demonstrated [22][23]. This strategy allowed for the generation of perceivably tunable forces, whilst also separating the user from the high voltage components. This approach proved to be particularly suitable for rendering soft-body tactile interactions.

This paper presents ongoing improvements to an existing system [23] by introducing a new DEA design which is more compact and able to generate higher forces, as well as presenting a new system that allows users to perform pinch gestures for two-fingers based tactile interactions with virtually generated objects.

2. DESIGN AND IMPLEMENTATION

System overview

The actuated tactile display system relies on the interplay among three distinct parts, described as input, processing and outputs. The system inputs are provided by a low cost optical hand tracking system such as Leap motion [1], which adopts stereo infrared cameras to create a representative three dimensional skeletal map of the users' hand in a virtual three dimensional space. This device can be used to track the position of the tips of the index and thumb fingers, during virtual pinching tasks. The second part of the system deals with data processing and the generation of control signals: it deduces the tactile feedback to be rendered to the user's fingertips, according to the finger position being rendered graphically. The system's output comes in the form of both a tactile response conveyed by the fingertip-mounted tactile display and a visual response displayed by the monitor. Figure 1 outlines this system architecture, with figure 2 providing a labelled snap shot of the system in use.

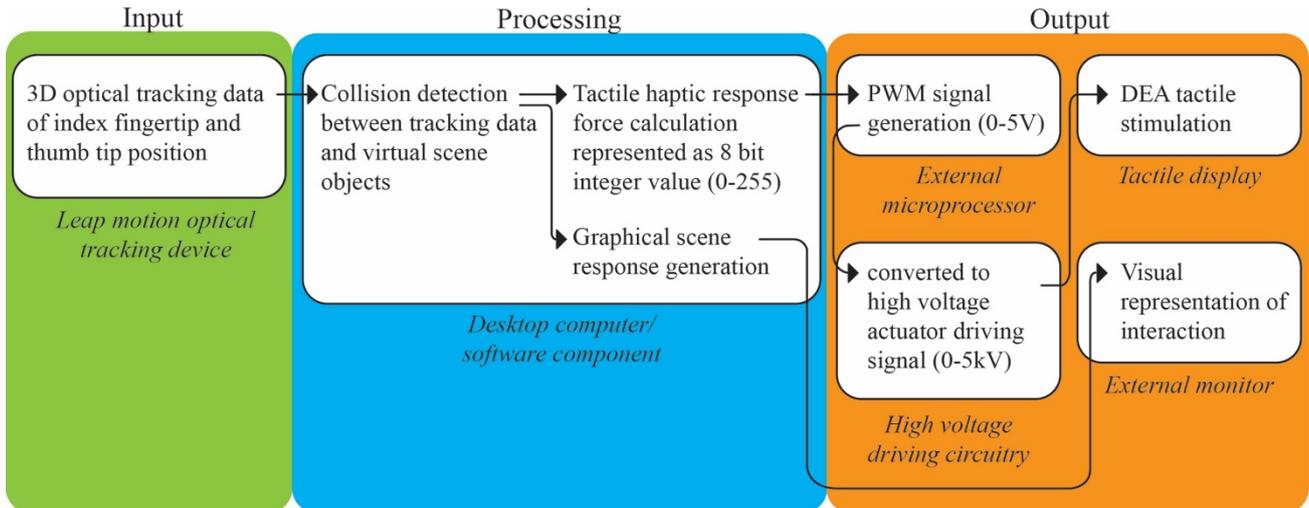


Figure 1. System architecture diagram showing system inputs, processes and outputs.

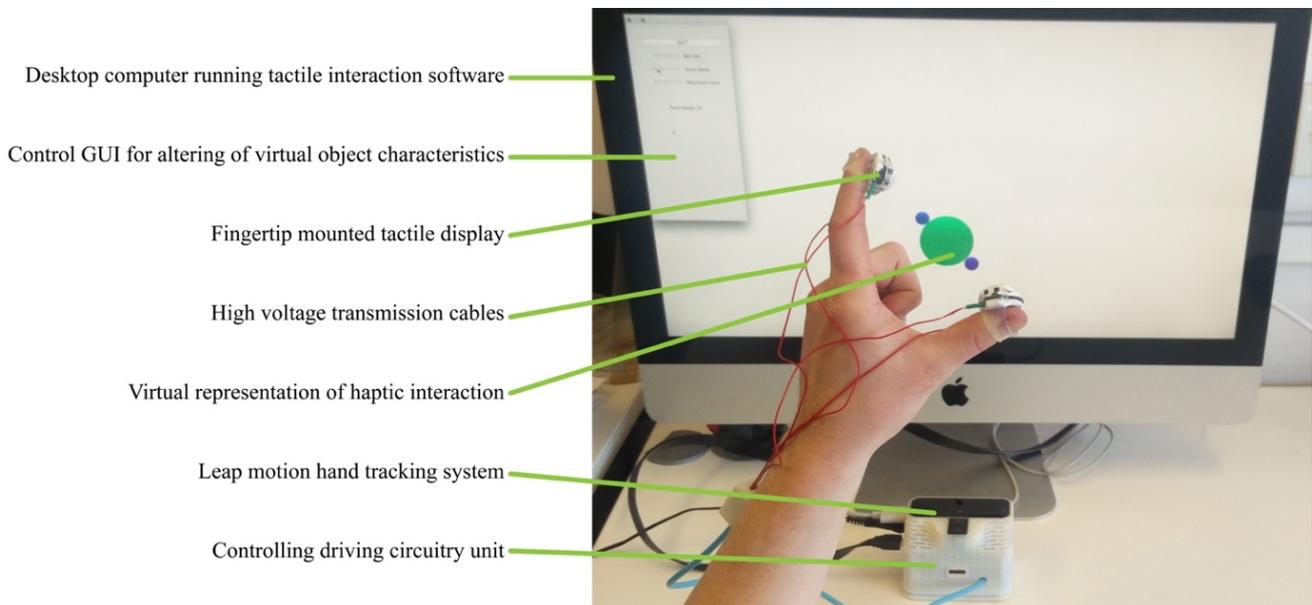


Figure 2. Labelled image of the developed tactile haptic display system.

Optical tracking system for the spatial position of fingers

While several optical systems are available for 3D fingertip tracking, such as the Kinect by Microsoft [2] and the Duo MLX by Code laboratories [24], the Leap Motion device (Figure 3) was used here as it is envisaged that this type of fingertip tactile display is more suitable for interaction with virtual models and scenes at a smaller scale and in low-cost portable systems. Moreover, the Leap Motion device has a high accuracy of fingertip tracking, higher than that achievable with the Kinect system at this use scale [25], [26]. Other advantages of the Leap Motion tracking system include the availability of a large programming support community.

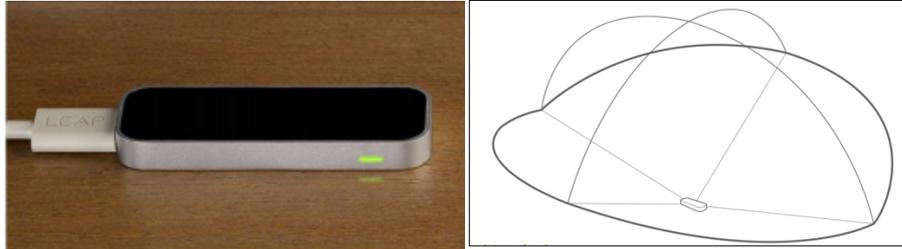


Figure 3. Leap Motion hand tracking system (left); Leap Motion interaction area (right).

The main limitation of the Leap Motion device, as compared to the Kinect and other high-cost motion tracking systems, is that it only caters for interaction within an area of 0.2 m^3 in the form of an inverted pyramid from the device's stereo infrared cameras. Guna et al [26] have published a detailed analysis of the precision and reliability of the Leap Motion tracking system [26]. They compared the Leap Motion system against a higher cost high precision optical motion tracking system (Qualisys Motion Capture [27]) for both static and dynamic tracking scenarios. Results from that study demonstrated that for static situations the Leap Motion device could record fingertip positions with a sub 0.5 mm standard deviation, but for dynamic scenarios inconsistent and unreliable values were obtained, especially for tracking of objects further than 300mm from the device and at the extremities of the device's field of view. Initial tests with the Leap motion system indicated that it was satisfactory when providing motion tracking for interaction with virtual models within a volume of $200 \times 200 \times 200 \text{ mm}^3$.

Control software

The software component was responsible for performing detection of interactions (contact and deformation) between the virtual fingers (controlled with data received from the Leap Motion hand tracking device) and the soft virtual object being explored. To do this the Java programming language was adopted, as it facilitates the use of third party libraries which cater for the rapid development of the graphical elements and provide the serial communication resources for the communication protocol between a computer (which runs the Java program) and an external microprocessor (which drives the actuators).

A software environment was developed that allowed various virtual objects of different sizes with controllable graphical and tactile properties to be created. Using this it was possible to modulate the rate at which a force was applied to the user's finger as well as the maximum force that was applied. It was also possible to generate areas within the virtual environment where users can place their hand to receive a pre-programmed tactile response, or trigger more complex signals which require a frame rate higher than 60 Hz (the graphical response frame rate of the controlling programme), to be rendered by the microprocessor. A program was also developed to control the DEA device for bench testing.

Control circuitry

The control circuitry was responsible for generating the high voltage signal that drives the actuator. In the proposed system an Arduino Uno [28] with the Atmega 328 chipset [29], which acted as the external microcontroller, was used. This device was connected to a desktop computer which transmits integer values via a wired USB serial interface. These 8 bit (0 to 255) values were converted linearly by the microprocessor to a 0-5 V linearly proportional Pulse Width Modulated (PWM) signal. Before this voltage signal was converted into the high driving voltage signal required by the DEA, it was smoothed. To do this, a simple low-pass filter, consisting of a 150Ω resistor and $4.7 \mu\text{F}$ capacitor, was used.

The smoothed PWM signal was then applied to a buffer (voltage follower), which had two functions; firstly, to ensure a separation between the microprocessor and the high voltage supply circuitry; secondly, to provide the amperage required

by the low-to-high voltage converter used to boost the voltage. The converter used was the EMCO Q50-5R [30], which linearly converted the 0-5 V input voltage to the 0-5 kV actuator driving voltage. One of the advantages of the EMCO Q50-5R component is its relatively small volume (~12 mm³), which enables multiple converters to be placed within a relatively small space. The control circuitry in most recent version of the system was designed to individually control two DEA devices simultaneously, although the system of course can easily be scaled up, to add more independent channels (to control more tactile actuators placed on more fingers).

Design of the soft tactile stimulation actuator

The conceived tactile display developed in this work adopted a technology known as Hydrostatically Coupled DEAs (HC-DEAs) [31]. This concept makes it possible to separate the user from the high voltage driving components of the device. It does this by coupling a passive membrane, which is in contact with the user’s finger, with a DEA active membrane through an incompressible silicone gel. Effectively we have a soft bubble interface that moves up and down to apply a force to the user’s finger (Figure 4).

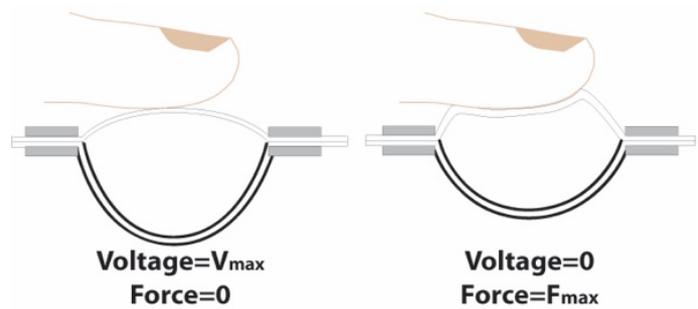
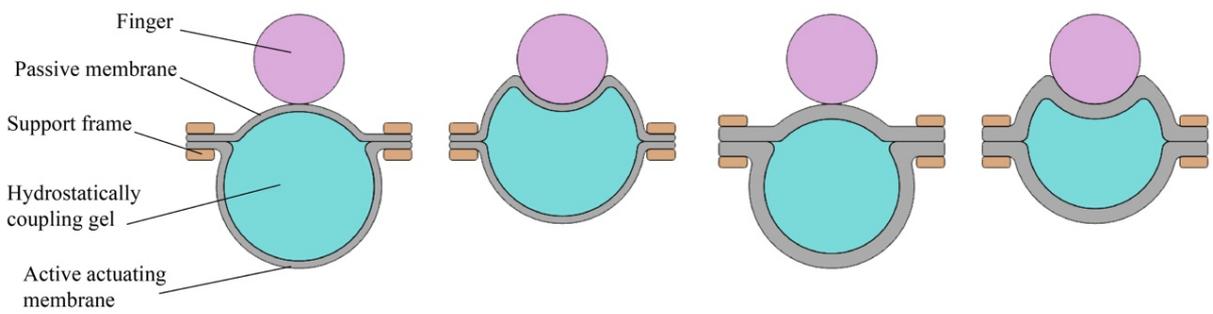


Figure 4. Schematic drawings of the interaction between the finger and the soft tactile display

As shown in the figure, the actuator applies full force to the user’s finger when no voltage is applied. The force is then reduced through the application of a voltage. The passive force generated by this device is due to the elastic modulus of the dielectric elastomer membrane and its thickness. In previous HC-DEA-based tactile displays, the dielectric elastomer membrane consisted of the 3M VHB 4910 film, pre-stretched by a ratio of four. This material has been demonstrated to achieve optimal actuation strains when bi-axially pre-stretched by a by a stretch ratio of four [32] and has been shown to generate forces of up to 0.6 N in previous HC-DEA configurations [22].

Having a greater difference between the minimal and maximal forces generated by the actuator, when the actuator transitions from a state of full actuation to a resting state (no voltage applied) would increase the range of tactile pressure sensations that the device can render upon the user.



Thin membrane lower force generating HC-DEA Thick membrane higher force generating HC-DEA

Figure 5. Labelled schematic illustrating higher force generating HC-DEA concept with thicker membrane.

To increase the force using the same dielectric elastomer material, it was necessary to increase the actuating membrane's thickness. However, when adopting a thicker membrane there is a requirement to significantly increase the driving voltage, in order to achieve the same compressive stress p :

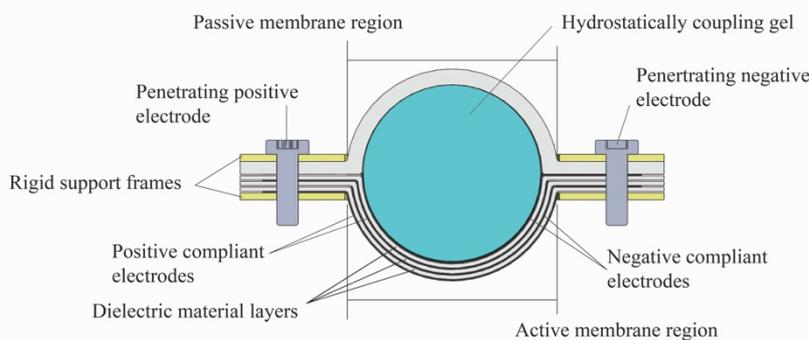
$$p = \epsilon\epsilon_0 E^2 = \epsilon\epsilon_0 (V/d)^2$$

where ϵ is the relative dielectric constant of the material, ϵ_0 is the permittivity of free space (8.85×10^{-12} F/m), E is the electric field, V is the voltage and d is the membrane's thickness [15].

One methodology to avoid increasing the voltage, while increasing the overall thickness, is to split the active membrane into layers which have alternating compliant electrode polarities. This idea has been employed in a number of other DEA actuator designs [33]–[35] and is commonly referred to as stacked DEAs. This means the HC-DEA with a multilayer active membrane can be actuated with a voltage lower than that required by an HC-DEA with an active membrane with equivalent thickness, made of a single layer. The main issue concerning this solution lies within the increased complexity of manufacture and ensuring a suitable inter-layer insulation.

In this work, the active membrane was assembled using three layers of the 3M VHB 4910 film [36] (Figure 6). The compliant electrodes consisted of carbon grease (MG Chemicals, Carbon Conductive grease 846 [37]) applied with a thick foam roller and a stencil. For the passive membrane, three layers of VHB film with the same prestretch were used to balance the elastic forces. To create the bubble structure, the passive membrane was deformed with a negative pressure chamber. A volume of 1 ml of a silicone gel (MG Chemicals, Translucent silicone grease 8462 [38]) was then injected into the formed cavity, using a syringe. The active membrane layers were then placed on top, and the negative pressure was released. Support frames to maintain the bubbles structure were then added. These were laser cut from 0.5 mm-thick PMMA sheets.

Labeled cut view of multilayer HC-DEA



Trimetric cut view

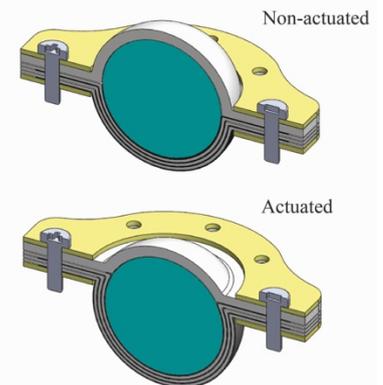


Figure 6. Labelled schematic illustrating multilayer HC-DEA concept

An additional change with respect to earlier versions consisted of the fact that the biaxial prestretch applied to the elastomer films during manufacturing was reduced to 300%. Indeed, that prestretch was applied when the film was still in a planar configuration, before the vacuum was applied to create the dome-like shape of the membrane. As the latter process further increases the stretch to a higher value, it was realised that it is opportune to reduce the planar pre-stretch, so as to avoid the excessive stretch of the membrane in the final 3D arrangement, which would cause excessive stiffening, thus reducing its actuation performance.

Actuator casing and fingertip attachment method

The actuator was embedded into a custom casing. The casings functions were to provide a barrier between the actuator and the high voltage components of the device, hold the device upon the finger in a comfortable and secure fashion and to not impede tracking by the optical tracking system. The casing was produced using a 3D printer with an insulating black plastic resin of unknown formulation. To hold the device in position against the fingertip in a comfortable fashion, custom compliant silicone finger straps of a range sizes were developed.

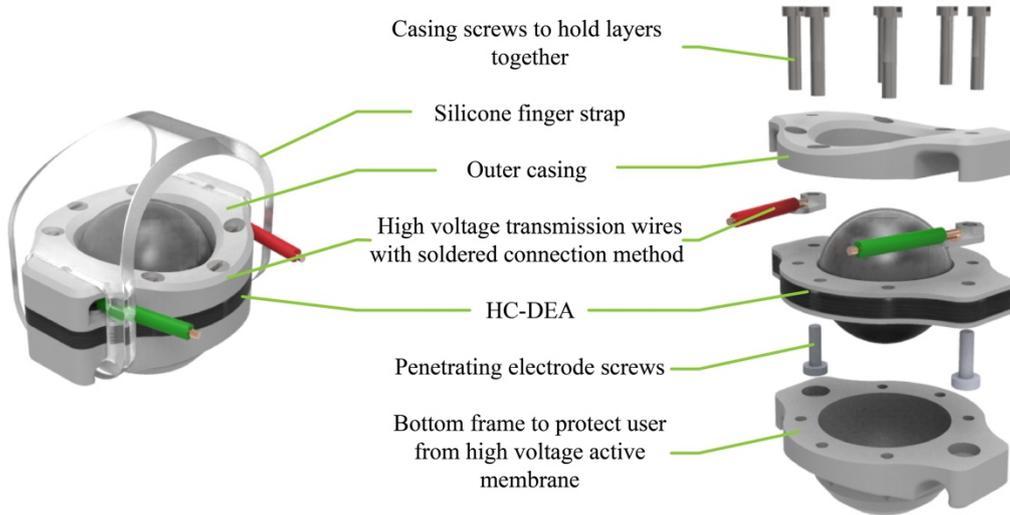


Figure 7. Labelled schematic illustrating the construction of the tactile device

3. EXPERIMENTAL TESTING OF HC-DEA

Bench testing

To measure the force output against the voltage input uniaxial tests were performed, using an Instron dynamometer with a 10 N load cell [39] (Figure 8).

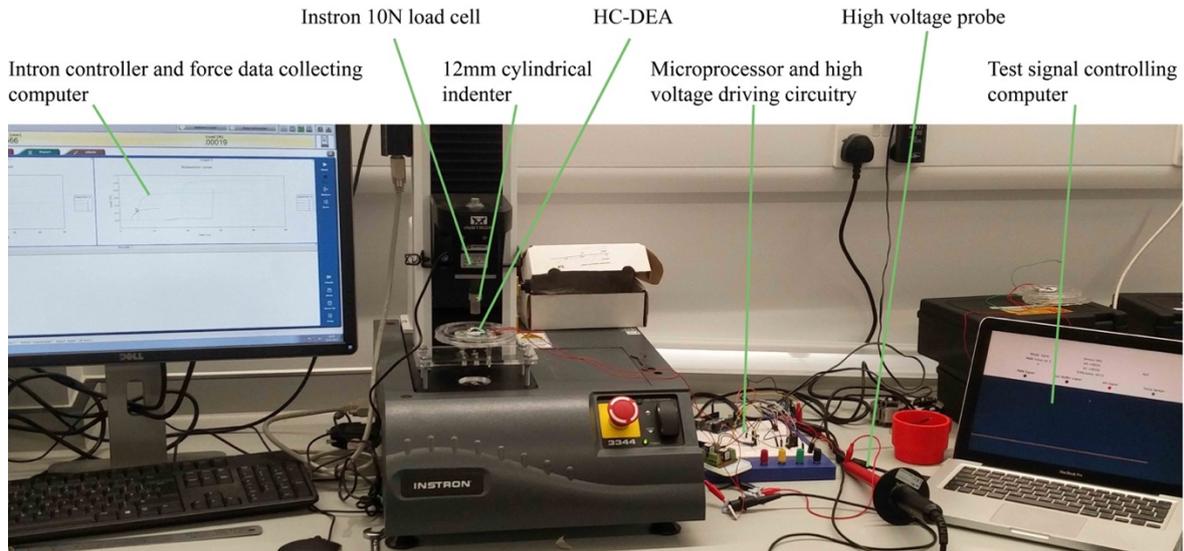


Figure 8. Labelled image demonstrating experiment setup for load tests of HC-DEA tactile device

The actuator was driven with 4 kV (200 PWM value) and the dynamometer's bar was brought in contact with the actuator's passive membrane, obtaining a 0.05 N bias threshold force. When this threshold was reached, the voltage across the actuator was decreased programmatically in steps of 0.02 kV (5 PWM value) every 1000 ms. The test signal applied over the duration of the test is illustrated in figure 9. The load cell was equipped with a cylindrical indenter having a circular base with a diameter of 12 mm. The force measured by the cell was acquired at a rate 100 samples per second.

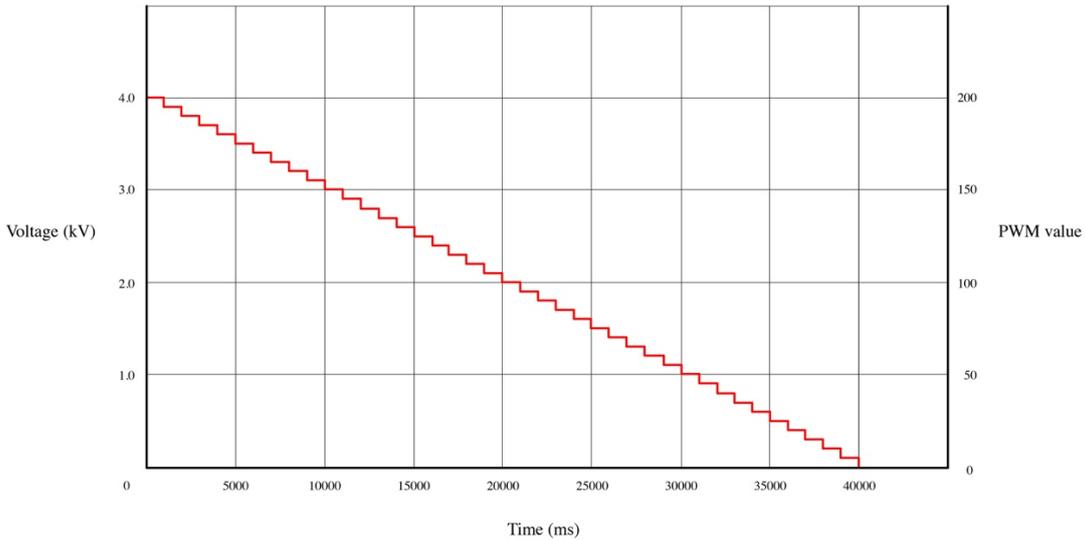


Figure 9. Graph outlining actuating signal over load cell test duration.

Two groups of actuators were tested. The first group (Group A) comprised three actuators which had been manufactured within two hours of the beginning of the test. The second group (Group B) included two actuators fabricated two days prior to testing. The motivation for making such a comparison was to quantify the performance drop off, due to the significant stress relaxation that it is well known to occur in the 3M VHB acrylic films [16], [17].

Force against Time results for step tests performed on multilayer HC-DEAs

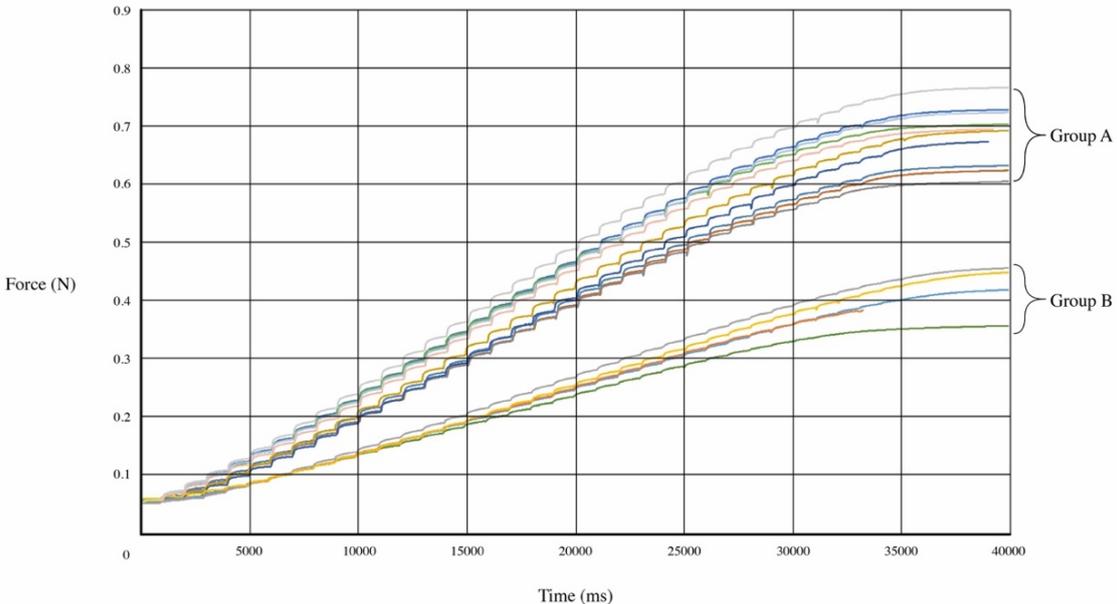


Figure 10. Graph outlining results of load cell testing

Figure 10 shows results for each of the two groups of actuators that were tested. As expected, there was a significant difference between the two groups. Group A's actuators have a larger force range over the period of testing, owing to less stress relaxation.

To deduce an approximate relationship between the force generated and the voltage applied for newly made actuators, the force data collected from group A were averaged. The resulting average data were then plotted against the corresponding applied voltage values, as displayed in figure 11.

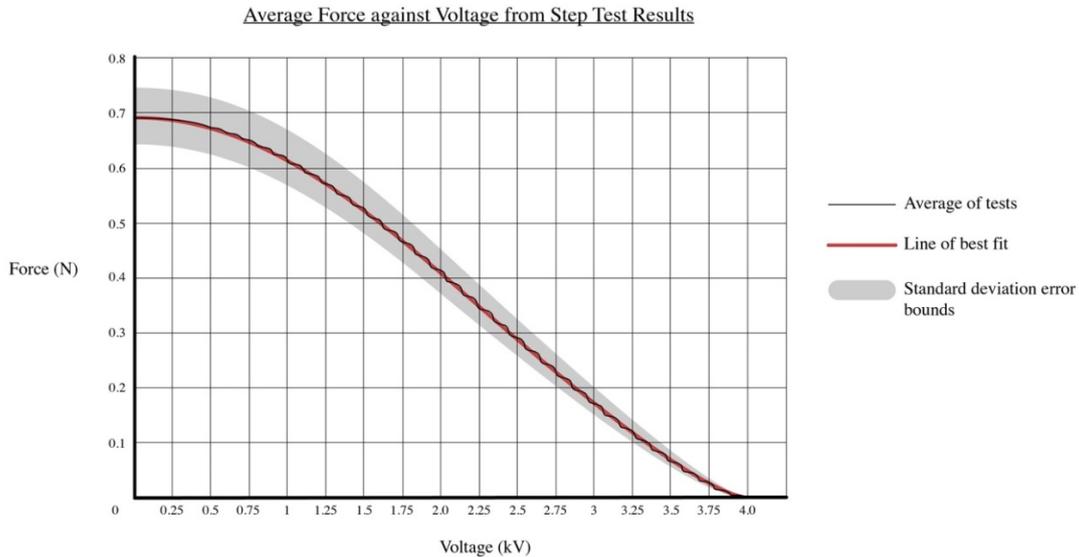


Figure 11. Average force generated by the multilayer HC-DE as a function of the applied voltage

Preliminary user testing

Figure 12 shows a user performing a pinch motion on a virtual soft body object. During initial tests, it was observed that participants found it difficult to locate a static object within the virtual 3D space using the monitor and the tactile display. The program was then modified slightly to make the virtual object track to the midpoint between the index finger and the thumb. With this change, users could easily perform a pinching motion upon the object being rendered.

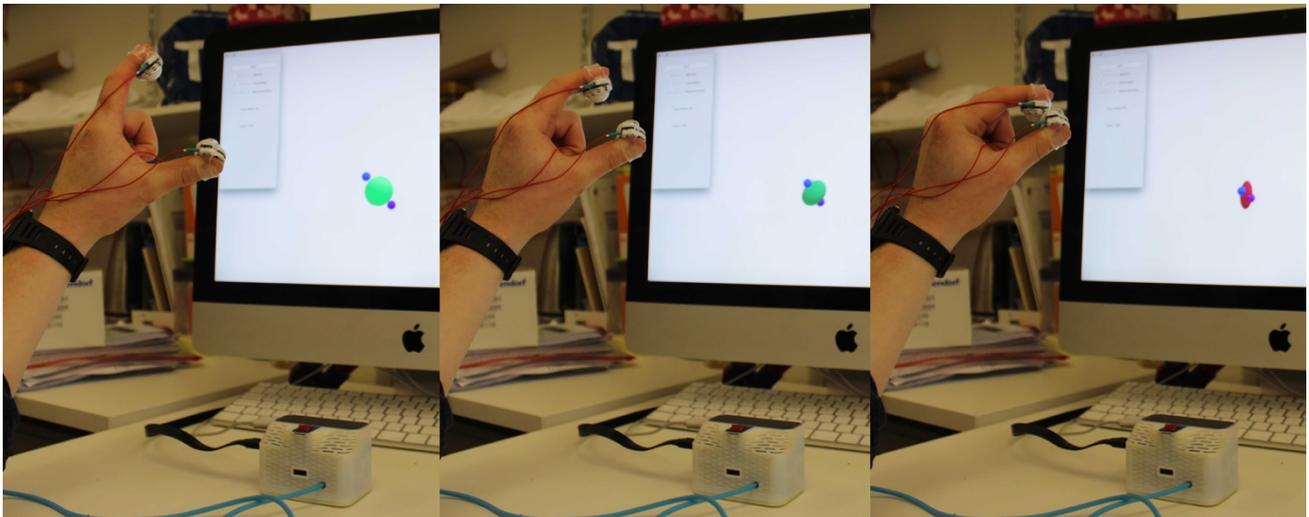


Figure 12. Images demonstrating a participant performing a pinch gesture upon a virtual soft body object. A video demo of the system being used can be watched at the following web link: https://www.youtube.com/watch?v=vj_wsnQt8So

It was possible to modulate the rate at which force was applied upon the user's finger as well as to alter the maximum force that was applied. Within the environment, shown in figure 12, was created a spherical object that deformed in a plane perpendicular to thumb and fingertip positions. As this sphere object tracks to the midpoint of these positions, the size of the sphere was altered to fit users that had different maximal distances between the thumb and index finger. As the sphere deformed over the pinch motion applied by the user, the force applied to the users thumb and index finger was ramped up, until a maximum force is reached. This maximum and rate of force application can be controlled within the programme. Participants described the sphere as harder or stiffer when higher forces were applied to user's fingertip at smaller deformations. Comparatively, the sphere was described as softer and more deformable when the maximum force applied was spread over a larger deformation.

It was also found that the Leap motion hand tracking device sometimes produced inaccurate data pertaining to fingertip positions, which would therefore not make it suitable for use in delicate tasks within the virtual environment. Nevertheless, for the purposes of initial testing with this prototype it was considered sufficiently adequate, particularly for pinch tasks occurring in an axis parallel to the top surface of the tracking device.

4. CONCLUSIONS AND FUTURE DIRECTIONS

The multilayer, thicker actuating membrane HC-DEA performed better than the previous single-layer HC-DEA described previously. We obtained an average maximum force range of 0.7 N over a smaller applied voltage range of 4 kV, compared to previous 0.6 N over a 4.5 kV range. This results confirms that, as anticipated that the multilayer active membrane is a better approach in HC-DEA design.

A drop in performance, in terms of force generation range, was assessed for the group of actuators that had been allowed to rest for two days before the testing. This performance drop-off was due to the stress relaxation of the stretched VHB acrylic film. To work around this issue, active membranes made of silicone are regarded as a potential alternative, but there are still several issues that remain unresolved that relate the higher stiffness of the material and a difficulty in bonding multiple layers together, as well as properly securing them to the support structure.

From the initial tests conducted with the tactile actuator within the virtual 3D testing environment it appears that this device is promising as a novel technology for human computer interactions. Further tests concerning perceptual thresholds and user experience should be conducted to explore the full potential of this tactile interface.

REFERENCES

- [1] Unknown, "Leap Motion," Leap Motion, <http://leapmotion.com/> (23 February 2017).
- [2] Unknown, "Kinect - Windows app development," Microsoft, <https://developer.microsoft.com/en-us/windows/kinect> (23-Feb-2017).
- [3] T. H. Massie and J. K. Salisbury, "The PHANToM haptic interface: A device for probing virtual objects," *Proceedings of the ASME Dynamic Systems and Control Division*, 295–301 (1994).
- [4] Unknown, "Geomagic Touch (formerly Geomagic Phantom Omni) Overview," Geomagic, <http://www.geomagic.com/en/products/phantom-omni/overview> (23 February 2017).
- [5] T. Koyama, I. Yamano, K. Takemura, and T. Maeno, "Multi-fingered exoskeleton haptic device using passive force feedback for dexterous teleoperation," *IEEE/RSJ International Conference on Intelligent Robots and Systems* 3, 2905–2910 (2002).
- [6] Unknown, "CyberGrasp," CyberGlove Systems LLC, <http://www.cyberglovesystems.com/cybergrasp/> (23 February 2017).
- [7] Unknown, "Dexta Robotics" Dexta Robotics, <http://www.dextarobotics.com/> (23 February 2017).

- [8] A. M. Murray, R. L. Klatzky, and P. K. Khosla, "Psychophysical Characterization and Testbed Validation of a Wearable Vibrotactile Glove for Telem Manipulation," *Presence* 12(2), 156–182 (2003).
- [9] Unknown, "CyberTouch," CyberGlove Systems LLC, <http://www.cyberglovesystems.com/cybertouch/> (23 February 2017).
- [10] M. Slater, "Touching the void: exploring virtual objects through a vibrotactile glove," *The International Journal of Virtual Reality* 11(2), 19–24 (2012).
- [13] T. R. Coles, N. W. John, D. Gould, and D. G. Caldwell, "Integrating Haptics with Augmented Reality in a Femoral Palpation and Needle Insertion Training Simulation," *IEEE Transactions on Haptics* 4(3), 199–209 (2011).
- [14] M. O. Culjat, C. H. King, M. L. Franco, C. E. Lewis, J. W. Bisley, E. P. Duston and W. S. Grundfest, "A tactile feedback system for robotic surgery," *International Conference of the IEEE Engineering in Medicine and Biology Society*, 1930–1934 (2008).
- [15] R. Pelrine, R. Kornbluh, Q. Pei, and J. Joseph, "High-Speed Electrically Actuated Elastomers with Strain Greater Than 100%," *Science* 287(5454), 836–839 (2000).
- [16] F. Carpi, D. De Rossi, R. Kornbluh, R. Pelrine, and P. Sommer-Larsen, "Dielectric Elastomers as Electromechanical Transducers," Amsterdam: Elsevier, (2008)
- [17] P. Brochu and Q. Pei, "Advances in dielectric elastomers for actuators and artificial muscles," *Macromolecular Rapid Communication* 31(1), 10–36, (2010).
- [18] F. Carpi, S. Bauer, and D. De Rossi, "Stretching Dielectric Elastomer Performance," *Science* 330(6012), 1759–1761, (2010).
- [19] I. Koo, K. Jung, J. Koo, J. Nam, Y. Lee, and H. R. Choi, "Wearable tactile display based on soft actuator," *Proceedings IEEE International Conference on Robotics and Automation*, 2220–2225 (2006).
- [20] R. Zhang, A. Kunz, P. Lochmatter, and G. Kovacs, "Dielectric Elastomer Spring Roll Actuators for a Portable Force Feedback Device," *Symposium on Haptic Interfaces for Virtual Environment and Teleoperator Systems* 14, 347–353 (2006).
- [21] E. Knoop and J. Rossiter, "A compliant soft-actuator laterotactile display," *Smart Materials and structures* 24(4), 34–35 (2015).
- [22] G. Frediani, D. Mazzei, D. De Rossi, and F. Carpi, "Wearable Wireless Tactile Display for Virtual Interactions with Soft Bodies," *Frontiers in biotechnology* 2, (2014).
- [23] G. Frediani, H. Boys, S. Poslad, and F. Carpi, "Enabling Wearable Soft Tactile Displays with Electroactive Smart Elastomers," *EuroHaptics Perception devices control and applications* 9775, 326–334 (2016).
- [24] Unknown, "DUO MLX - USB Stereo Camera." Code laboratories, <https://duo3d.com/product/duo-minilx-lv1> (23 February 2017).
- [25] F. Weichert, D. Bachmann, B. Rudak, and D. Fisseler, "Analysis of the Accuracy and Robustness of the Leap Motion Controller," *Sensors* 13(5), 6380–6393 (2013).
- [26] J. Guna, G. Jakus, M. Pogačnik, S. Tomažič, and J. Sodnik, "An analysis of the precision and reliability of the leap motion sensor and its suitability for static and dynamic tracking," *Sensors* 14(2), 3702–3720 (2014).
- [27] Unknown, "Qualisys | Motion Capture Systems," Qualisys, <http://www.qualisys.com/> (23 February 2017).
- [28] Unknown, "Arduino - ArduinoBoardUno," Arduino, <https://www.arduino.cc/en/Main/arduinoBoardUno> (23 February 2017).

- [29] Unknown, "ATmega328 - Microcontrollers and Processors," Atmel, <http://www.microchip.com/wwwproducts/en/ATmega328> (23 February 2017).
- [30] Unknown, "Q50-5R PDF Datasheet," Datasheets360, <http://www.datasheets360.com/pdf/-1825410290502444559> (23 February 2017).
- [31] F. Carpi, G. Frediani, and D. De Rossi, "Contractile Hydrostatically Coupled Dielectric Elastomer Actuators," *IEEE/ASME Transactions on mechatronics* 17(5), 987–994 (2012).
- [32] S. J. A. Koh, T. Z. J. Li, X. Zhao, W. Hong, J. Zhu and Z. Suo, "Mechanisms of large actuation strain in dielectric elastomers," *Journal of polymer science: Part B Polymer Physics* 49(7), 504–515 (2011).
- [33] P. Lotz, M. Matysek, and H. F. Schlaak, "Fabrication and Application of Miniaturized Dielectric Elastomer Stack Actuators," *IEEE/ASME Transactions on mechatronics* 16(1), 58–66 (2011).
- [34] P. Rasti, H. Hous, H. F. Schlaak, R. Kiefer, and G. Anbarjafari, "Dielectric elastomer stack actuator-based autofocus fluid lens," *Applied Optics* 54(33), 9976–9980 (2015).
- [35] G. Kovacs, L. Düring, S. Michel and G. Terrasi, "Stacked dielectric elastomer actuator for tensile force transmission." *Sensors and Actuators A: Physical* 155(2), 299-307 (2009).
- [36] Unknown, "3MTM VHB™ Tape 4910 Clear, 3/4 in x 36 yd 40.0 mil, 3 per case." 3M, http://solutions.3m.com/wps/portal/3M/en_US/Adhesives/Tapes/Products/~3M-VHB-Tape-4910-Clear-3-4-in-x-36-yd-40-0-mil-3-per-case?N=6105+3291638463+4294870937&rt=rud (23 February 2017).
- [37] Unknown, "846 - Carbon Conductive Grease - Conductive Greases," MG Chemicals, <http://www.mgchemicals.com/products/greases-and-lubricants/conductive-greases/carbon-conductive-grease-846> (23 February 2017).
- [38] Unknown, "8462 - Translucent Silicone Grease - Dielectric Grease," MG Chemicals, <http://www.mgchemicals.com/products/greases-and-lubricants/dielectric-grease/silicone-8462> (23 February 2017).
- [39] Unknown, "Instron 10 N Static Load Cell - Instron," Instron, <http://www.instron.co.uk/en-gb/products/testing-accessories/load-cells/static/2519-series-s-beam/2519-10n> (23 February 2017).