Towards shear tactile displays with DEAs

Lars Espen Knoop[*,a,b], Jonathan Rossiter[a,b]

[a]Department of Engineering Mathematics, University of Bristol, University Walk, Bristol BS8 1TR, UK;
[b]Bristol Robotics Laboratory, T Block, Frenchay Campus, Coldharbour Lane, Bristol, BS16 1QY, UK

ABSTRACT

Much research has been done on the development of tactile displays using Dielectric Elastomer Actuators (DEAs). It has been argued that they offer the potential to create low-cost full-page tactile displays — not achievable with conventional actuator technologies. All research to date has considered tactile elements moving perpendicular to the skin and thus applying a normal force distribution.

In contrast to previous work, we have investigated the use of laterally moving tactile elements that apply shear forces to the skin. This allows for the areal expansion of the DEA to be exploited directly, and a tactile display could be made with no elements moving out of the plane. There is evidence that humans are very sensitive to shear force distributions, and that in some cases a shear stimulus is indistinguishable from a normal stimulus.

We present a prototype shear tactile display actuated by a DEA, and demonstrate that the DEA can generate the necessary forces and displacements. We also present and discuss different display topologies.

Keywords: Tactile display; Lateral stimulation; Dielectric elastomer; Shear force; Electroactive polymer.

1. INTRODUCTION

In the same way that a visual display can show any visual information, a tactile display will allow for presentation of any tactile information. Tactile displays show great potential for enhancing user interaction with electronic devices. Almost all information in a smartphone, for example, is conveyed through the screen (visual) and speaker (audio) with only very coarse information being provided through the sense of touch. Tactile interaction could be used together with visual interaction for an improved user experience, but it could also replace visual interaction in cases where it is impractical or impossible to look at the device being used.

A full-page tactile display will in general require a large array of hundreds or thousands of actuators, in the same way that a visual display requires a large array of pixels. The mechanical complexity of conventional actuator technologies makes them unsuited for such applications.

Much work has been done looking at the use of ElectroActive Polymers (EAPs), in particular DEAs, as actuators for tactile displays. DEAs have many desirable properties including large strains, high power density and very low mechanical complexity [1]. It has been proposed that DEAs could deliver the technology required to realise the 'holy braille' [2, 3] of virtual Braille displays, a low-cost full-page device.

A number of different designs for DEA tactile displays have been investigated, including stack actuators [4–6], tubular actuators under Braille dots [7–9], embossed DEA bumps [10–12], and hydrostatically [13–15] or rigidly [16] coupled DEA bumps. For a more in-depth summary the reader is directed to a recent review paper [17].

All research to date has considered tactile elements moving perpendicular to the skin surface. In contrast to previous work, we here investigate the use of an array of elements moving laterally against the skin and applying shear forces. There is evidence suggesting that this may be a highly effective means of tactile stimulation.

*espen.knoop@bristol.ac.uk

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1.1 Shear tactile stimulation

The Tactile Contact Lens [18, 19] is a passive device that converts normal surface undulations into lateral pin movements. Studies show that the Tactile Contact Lens improves the sensitivity of the fingertip, suggesting that shear tactile stimulation could be very effective.

Most of the research into shear tactile stimulation has been done by Hayward [20, 21] with the development of a tactile display made up of an 8×8 element array of piezo cantilever beams (spacings of 1.2 mm and 1.6 mm in the respective directions) that move laterally against the skin. The latest version of the device, *Latero*, is manufactured by Tactile Labs. In Hayward's work is argued that shear stimulation in many cases feels indistinguishable from normal stimulation [20].

Haptic stimulation can be split into a tactile part stimulating the sense of touch and a kinaesthetic part applying forces to the joints and muscles [22]. With shear tactile stimulation we are concerned with the local distribution of shear force over the fingertip surface. This is different from the application of a global net shear force to the finger, i.e. the kinaesthetic element.

There is also a distinction between tactile displays where there is slip between the finger and the display (e.g. relief maps) and tactile displays where there can be no slip [20]. Shear tactile displays fall into the latter category, as the device needs to create a distribution of shear forces on the fingertip. This makes them potentially suited for wearable tactile displays.

1.2 Requirements

The requirements of a tactile display are governed by the mechanical properties of the finger and the properties of the mechanoreceptors. The two-point discrimination distance, i.e. the spatial resolution, of the fingertip is ~ 1.0 mm so the array spacing of the tactile display should ultimately be similar to this [23].

Some experimental work has been done to characterise human sensitivity to shear tactile stimulation [24, 25], however this field is not well studied. It is therefore difficult to determine the requirements in terms of forces or strains for a shear tactile display. The actuators on the Latero device have unloaded displacements of ± 100 μm and generate blocking forces of 0.15 N. However, psychophysical studies [21] show little improvement from running the device at ~ 20 % power to running it at full power, which suggest that the thresholds for sensitivity are much lower.

1.3 Benefits of a DEA shear tactile display

DEAs undergo large areal expansions, and in a shear tactile display this could be exploited directly by coupling the areal expansion of the actuator to the areal expansion of the skin. This should allow for thinner and mechanically less complex tactile displays.

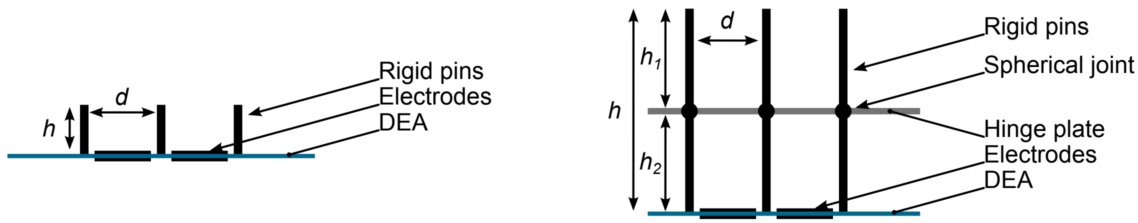
Compared to existing shear tactile displays that are either piezo-actuated [21] or servo-actuated [24], a DEA actuated display could have greatly reduced mechanical complexity and thus be made much smaller. The flexible actuator opens up for the development of completely flexible and wearable tactile displays, such as a tactile glove.

2. DEVELOPMENT

2.1 Mechanism design

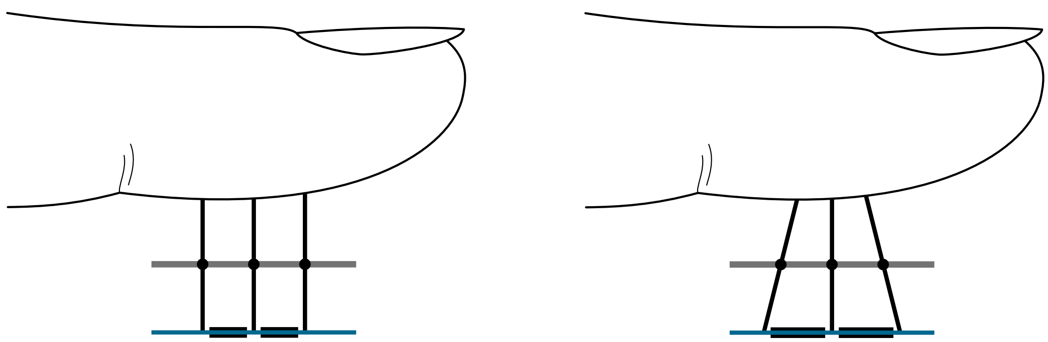
The simplest design for an array of laterally moving pins would seem to be the one seen in Fig. 1a, where vertical pins directly couple the movement of the DEA to the movement of the fingertip. In the ideal case, the strain applied to the finger would be equal to the strain in the DEA sheet. By actuating different areas of the DEA it would be possible to create shear force distributions.

However, lateral forces acting on the tops of the pins result in a torque at the pin bases — they act as cantilever beams — and due to the very low stiffness of the DEA sheet this greatly limits the shear force that can be generated. Even small lateral forces result in deflection of the pins rather than strains of the fingertip skin. This effect will decrease with smaller h, however in preliminary tests significant unwanted deflection was present at $h = 1.2$ mm using a single-layer acrylic dielectric elastomer (VHB 4905, 3M).



(a) Simple laterotactile display. (b) Hinged laterotactile display.

Figure 1: The proposed mechanism designs for the laterotactile display. The simple design is only able to generate small forces due to the flexibility of the DEA; this is remedied with the hinged design. In this paper we have implemented the hinged design.



(a) Relaxed state. (b) Actuated state.

Figure 2: 1-dimensional schematic drawing of the tactile display stimulating a finger in relaxed and actuated states. It can be seen that tensile strains in the DEA lead to compressive strains in the finger.

This problem is removed with the addition of a hinge plate as shown in Fig. 1b. Here, each pin is attached to the DEA as well as to a rigid hinge plate with spherical joints that allow for rotation while preventing translation. Because the pins are constrained to rotate about the spherical joint there is minimal torque and vertical force applied to the DEA. The operating principle of the hinge display is illustrated in Fig. 2. For the hinged display, it is seen that tensile strains in the DEA will result in compressive strains at the fingertip.

The hinged design also allows for tuning of the force/strain characteristics of the device. In the simple design (Fig. 1a) the force applied to the finger will be equal to the force output by the DEA, and the areal strain of the DEA will be equal to the areal strain of the finger. In the hinged design however (Fig. 1b) this can be tuned by varying the ratio $h_2 : h_1$. If h_1 becomes smaller the force applied to the fingertip will increase while the strain applied to the finger will decrease.

A further benefit of the hinged design is that the hinge plate isolates the finger from the electrodes.

In order to determine the relationship between the relative area strain of the DEA, ε_{DEA}, and the resultant relative area strain of the fingertip, ε_f, let us consider a DEA element centred between 4 pins. The 4 pins form a rectangle with side lengths of d_x and d_y respectively, and an area $d_x d_y$. The relative area strain is the ratio of the strained area over the original area. Under actuation, let us say that the sides of the DEA rectangle increase to $d_x + \delta_x$ and $d_y + \delta_y$. This gives a relative area strain of

$$\varepsilon_{DEA} = 1 + \frac{\delta_x}{d_x} + \frac{\delta_y}{d_y} + \frac{\delta_x \delta_y}{d_x d_y}. \tag{1}$$

It can be seen that the resulting side lengths for the rectangle on the finger surface are $d_x - \delta_x \frac{h_1}{h_2}$ and $d_y - \delta_y \frac{h_1}{h_2}$

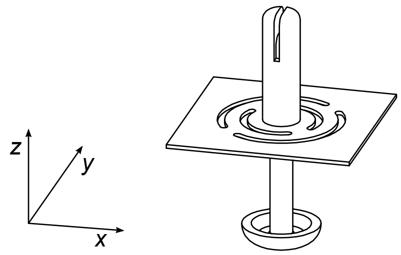


Figure 3: CAD model of a single element of the developed tactile display. The flexural hinge plate gives the pin 2 rotational degrees of freedom.

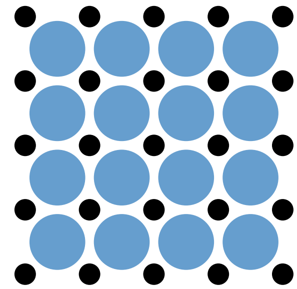


Figure 4: Layout of pins (black) and actuating electrodes (blue/lighter shading) for the prototype.

respectively, giving the relative area strain on the finger;

$$\varepsilon_f = 1 + \frac{\delta_x}{d_x}\frac{h_1}{h_2} + \frac{\delta_y}{d_y}\frac{h_1}{h_2} + \frac{\delta_x \delta_y}{d_x d_y}\left(\frac{h_1}{h_2}\right)^2 . \tag{2}$$

If δ is small relative to d then we can ignore the second order terms and obtain the relationship

$$\varepsilon_f = 1 - (\varepsilon_{DEA} - 1)\,\frac{h_1}{h_2}. \tag{3}$$

We can also take moments about the hinge to relate the force at the DEA (F_{DEA}) to the force at the fingertip (F_f), giving

$$F_f = \frac{h_2}{h_1} F_{DEA}. \tag{4}$$

In this way it is seen that by varying the ratio $h_1 : h_2$ the display can be tuned for increased force or increased strain. For example, if a single layer actuator was to be replaced with a multilayer actuator it might be advantageous to also increase h_1 so that the strain on the finger is increased as well as the force.

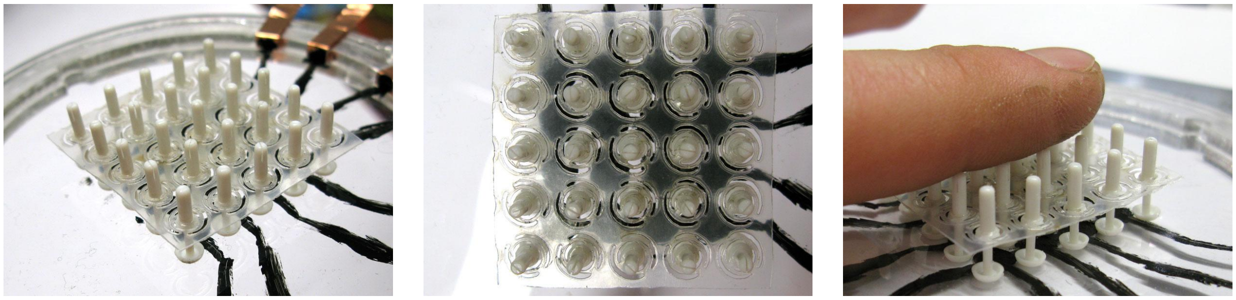
2.2 Prototype design and fabrication

A prototype tactile display was fabricated, implementing the hinged design presented in Fig. 1b. For the DEA we used a single-layer acrylic dielectric elastomer (VHB 4905, 3M), bi-axially prestrained 400 % and attached to a circular acrylic frame, resulting in an estimated elastomer thickness of 31 μm. Carbon grease electrodes (MG Chemicals), were brushed on through a laser-cut stencil.

There are substantial design and manufacturing challenges linked to designing a tactile display with a pin spacing of ~ 1 mm. Here, we have developed prototypes with pin spacings of 7 mm and 10 mm. Future work will look at miniaturisation of the design.

A CAD model of a single element of the developed prototype is shown in Fig. 3. Let us define a coordinate system to have the hinge plate in the x–y plane. The hinge is required to be flexible for rotations about the x- and y-axes while preventing translational movements in the x–y plane. This could be achieved with a ball joint, at the expense of high mechanical complexity. A better approach at this scale is a flexural hinge plate. We designed a flexural hinge in the form of a gimbal pattern manufactured from a flat sheet, as seen in Fig. 3. This pattern is flexible for rotations about the x- and y-axes while resisting translations in the x–y plane as required, and is also readily fabricated.

The hinge plate was laser cut from 200 μm thick polypropylene sheet, which provided a suitable rigidity. This sheet is flexible, yielding the possibility of using this design to make tactile displays that wrap around the finger. The combination of soft actuators and flexible materials shows exciting potential for the realisation of soft and compliant wearable devices.



(a) (b) (c)

Figure 5: Prototype DEA shear tactile display with 5×5 pins in a rectangular grid. The pin spacing is 7 mm.

The pins were made from Nylon, with a diameter of 2 mm above the hinge plate and 1 mm below the hinge plate. This was found to be sufficiently rigid for the application. As seen in Fig. 3, the base of the pins has a larger diameter which was attached to the DEA, held in place by the adhesion of the VHB. For the prototypes we set h_1 and h_2 both to 6.4 mm, so that the strain and force at the finger is equal and opposite to the strain and the force generated by the DEA. A jig was used to hold the pins vertical when attaching them to the VHB.

For maximum actuation, the active (electroded) area of the DEA should be maximised. The spacing between adjacent electrodes must however be sufficient to prevent breakdown. We used circular electrodes centred between groups of 4 pins as shown in Fig. 4. The electrode diameter was set to give 2 mm gaps between adjacent electrodes, i.e. 5 mm and 8 mm diameter respectively for the 7 mm and 10 mm pin spacings (labelled d in Fig. 1b). The electrodes were connected in a multiplexed grid, with rows of top electrodes and columns of bottom electrodes respectively connected together.

Photos of a prototype 5×5 element square array with 7 mm pin spacings are shown in Fig. 5.

3. CHARACTERISATION

One initial concern was whether the design could be scaled up to a large grid, or whether actuation would be adversely affected by having a large grid of actuators. With the prestrained VHB 4905 DEAs described previously, the unloaded strain of a circular 8 mm diameter electrode centred in a 80 mm diameter frame was compared to the unloaded strain of the same electrode centred in a 30 mm×30 mm square frame and found to be virtually identical for actuations up to 3 kV. In this way, the actuation of a single electrode will move 4 pins and affect the areal strain in 9 squares of the array. The strain distribution in the 80 mm diameter frame was also observed, and it could be seen that actuation only affected the local area of the DEA. In this way, it will be possible to scale the design up to large grids and characteristics of a single element will be identical to the characteristics of the grid. For this reason, characterisation tests were carried out on a single element i.e. a single circular electrode centred between 4 pins.

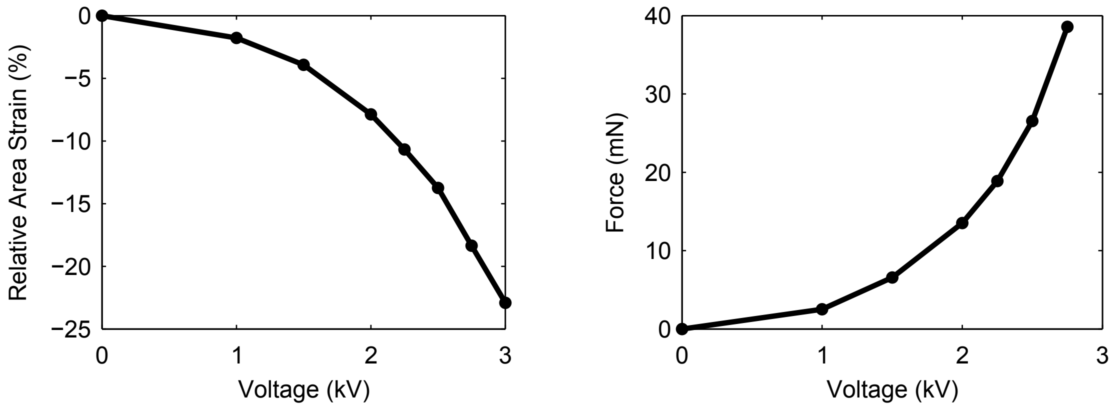
In order to characterise the tactile display we measured both the unloaded strain and the blocking force.

3.1 Strain

To characterise the displacement we wish to determine the strain of the tactile display. Tests were carried out on a single element, with a pin spacing $d = 10$ mm and a circular electrode with a diameter of 8 mm. The voltage was stepped up and down and the strain was determined by tracking the positions of the pins from a set of images. The driving voltages were generated using an EAP Controller (Auckland Bioengineering Institute).

The result is seen in Fig. 6a. It can be seen that there is an approximately negative squared relationship between voltage and strain, this would be expected from the squared relationship between voltage and electrostatic pressure for a DEA [1]. With an applied voltage of 3 kV a relative area strain of −23 % is achieved.

Preliminary analysis of the area strain of the electrode suggests that the electroded area experiences a significantly larger area strain than is transferred to the pins; it can be concluded that there are some losses in the gaps between the electrode and the pins.



(a) Strain, no-load.

(b) Blocking force.

Figure 6: Force and strain against voltage for the characterised prototype.

3.2 Force

We also wish to determine the blocking force that can be generated. Again, tests were carried out on a single element with a pin spacing $d = 10$ mm and with a circular 8 mm-diameter electrode. One pin (the ground pin) was rigidly fixed, and the blocking force was measured at the pin diagonally across from the ground pin (the moving pin). A load cell (LVS-5GA, Kyowa) was used to measure the blocking force at the tip of the moving pin. The voltage was stepped up and down.

The result is shown in Fig. 6b. Again, an approximately squared relationship between voltage and force is obtained. A voltage of 2.75 kV generates a blocking force of 39 mN.

3.3 Discussion

If we assume that the requirements of a shear tactile display are those of the Latero running at 20 % of the voltage, and that the force and strain change linearly with voltage, then we can estimate that we require a blocking force per unit length of 25 mN/mm and a relative area strain of 3.3 %.

If h_1 and h_2 were set so that a maximum strain of 3.3 % was obtained then a force per unit length of 19 mN/mm would be expected. This is close to the estimated value for the Latero device.

Moreover, the design of the tactile display makes it straightforward to replace the single-layer DEA with a multilayer DEA. Adding a second DEA layer should result in a doubling of the output force but have no impact on the strain; the force should increase proportionally with the number of layers.

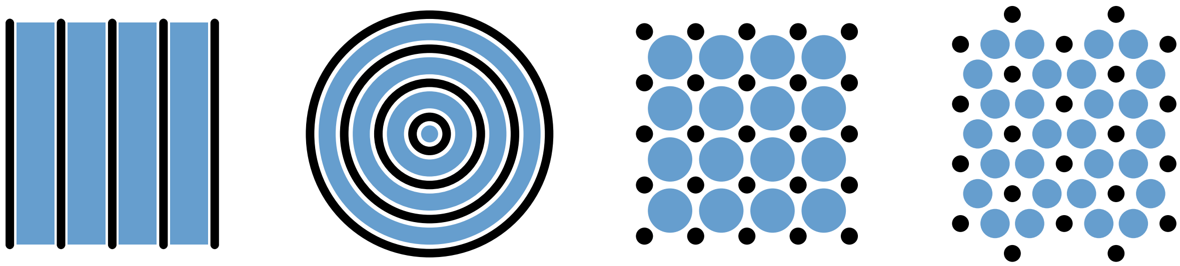
Preliminary tests of touching the prototype tactile display with a fingertip (Fig. 5c) have shown that it produces a clearly noticeable tactile sensation.

4. TOPOLOGIES

The prototypes developed here have used square grids of pins and actuators, with actuators between groups of four pins (Fig. 4). However, there are potentially other topologies that could have interesting properties.

For simple applications, a one-dimensional shear tactile display could be sufficient. As well as creating one-dimensional distributions of shear force, the use of temporally changing patterns would allow for the generation of tactile sensations moving across the display in either direction. A linear one-dimensional layout (Fig. 7a) could produce sensations of movement to the right or to the left.

An interesting avenue to explore is radial one-dimensional topologies (Fig. 7b), where concentric rings are actuated together. This should be able to create the sensation of dynamically changing circular bumps, with a possible application being the rendering of virtual pushbuttons.



(a) 1D, linear. (b) 1D, radial. (c) 2D, square. (d) 2D, hexagonal.

Figure 7: Possible topologies for 1-dimensional and 2-dimensional laterotactile displays. Finger-stimulating elements are shown in black and DEA electrodes are shown in blue/lighter shading.

A two-dimensional topology will allow for the creation of a larger range of tactile sensations — a 2D display with sufficient resolution would be able to emulate both the radial and the linear topologies. Two possible two-dimensional topologies are the rectangular grid (Fig. 7c) as used in this paper and the hexagonal grid (Fig. 7d). For the rendering of lines at different angles, the hexagonal grid would be expected to show a lower degree of angular quantisation, although for sufficiently small d this should not be of significance.

A more significant difference between the rectangular and the hexagonal topologies is that the hexagonal grid has a larger number of actuators for the same number of pins; the hexagonal grid has actuators centred between groups of 3 pins. Further study will be required to determine the optimal ratio of pins to actuators such that any strain pattern can be generated with a minimal amount of redundancy.

5. CONCLUSIONS

We have presented a first prototype of a shear DEA tactile display that applies lateral forces to the skin rather than normal forces. Evidence suggests that humans are very sensitive to distributions of shear force, and that in some cases the result feels indistinguishable from a normal force. The spatial resolution of the prototype, i.e. the pin spacing, is too great to render high resolution tactile images, but the operating principle is successfully demonstrated.

Our hinged design allows for tuning of the force/strain characteristics of the display to optimise the tactile sensation. We have shown that with the appropriate parameters it would be possible to create a version with suitable force and strain characteristics for shear tactile stimulation. In order to increase the force or strain, the single-layer DEA could be readily replaced with a multilayer DEA. The hinge plate also acts as a further insulating barrier between the DEA and the finger.

While the implemented display features a square grid of pins, we have also considered other possible topologies. In particular for the rendering of virtual buttons a one-dimensional radial display could be interesting to explore.

Further work will look at miniaturisation of the prototype as well as more in-depth characterisation. We will also aim to improve the understanding of the fundamentals underlying shear tactile stimulation.

ACKNOWLEDGMENTS

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