Follicular DEAs for two-way tactile communication

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ABSTRACT

Follicular structures in skin combine sensing and actuation in a soft and compliant continuous surface. We have developed a tactile display device inspired by this structure, using a Dielectric Elastomer Actuator (DEA). DEAs allow for combined sensing and actuation, making possible two-way tactile communication between the user and the device. The device can obtain tactile information about the environment, or a user touching it, and it can also present tactile information to the user. We characterise the sensing properties of the tactile display device, and perform classification of tactile stimuli. We demonstrate two-way tactile interaction between a user and the device.

Keywords: Tactile Display; Dielectric Elastomer Actuator; Bioinspired; Tactile Sensing; Tactile Stimulation; Self-sensing.

1. INTRODUCTION

In the follicular structure of skin, hairs protrude from a continuous skin surface that serves to protect the internal structure from the environment. The hairs pivot at the skin surface, and are actuated by muscles underneath the skin. Mechanoreceptors around the follicle sense movement of the hair [1]. Thus, the follicular structure provides both input (sensing) and output (actuation) functionality.

This structure could have many uses in robotics, such as tactile sensing through a 'skin' surface and smart conveyors. By using different appendages, a wide range of different behaviours could be achieved. With a relatively short and rigid appendage, the follicular skin structure can be used for a two-way tactile user interface providing tactile sensing as well as tactile feedback.

Two-way tactile communication could be between a user and a handheld electronic device e.g. providing tactile feedback to input gestures or interaction with a touch screen [2–4]. This could be used for automotive applications, where the driver needs to look at the road, and also for private interaction where the more public visual or auditory domains might be inappropriate.

Bidirectional tactile communication could also be between two users, for mediated social touch and telepresence. Current research includes transmitting tactile information through mobile phones [5, 6] or with a wearable sleeve [7].

In human-robot interaction, two-way tactile communication would allow for more natural and human-like interaction mechanisms. Gibbons *et al* [8] consider detection of tactile gestures with the Nao robot, and also tactile gesturing with the robot. A follicular robotic skin combining sensing and actuation could expand on the capabilities of natural skin. If applied to a robotic arm, the robot would gain a sense of touch and a person touching the robot would also receive tactile information from the robot e.g. about the state of the robot or the current risk level.

The development of more sophisticated tactile devices is currently limited by actuator technology, and it has been argued that electroactive polymers could allow for advances in this area [9]. In this paper, we demonstrate two-way tactile interaction using a follicular device with a Dielectric Elastomer Actuator (DEA). The DEA is used both for sensing and actuation. The compliance of the actuator means that it can undergo significant

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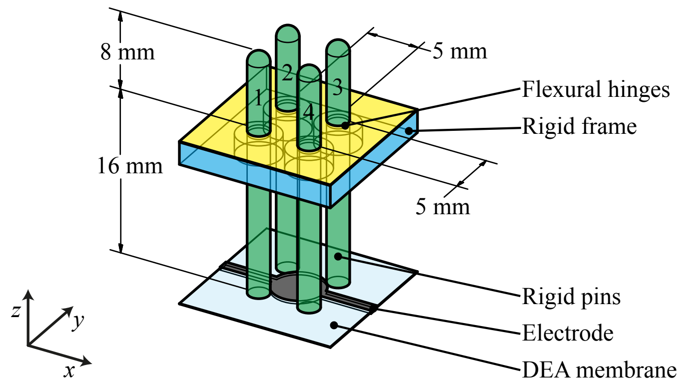


Figure 1: The follicular tactile display mechanism used in the LPD. The user touches the top of the pins, which move laterally (pivot at the hinge about the x- and y-axes) when the DEA is actuated. Pins have been numbered 1-4.

deformations while retaining functionality, allowing for it to move with the user. We first consider the detection of gestures (*tap, push, stroke*), and then combine this with tactile stimulation in a simple *call-response* demonstration.

There are many examples of DEAs being used in tactile applications, e.g. [10–14] and also in the mass-produced *ViviTouch* technology from *Artificial Muscle, Inc.*. The self-sensing properties of DEAs are frequently noted, but rarely exploited. Matysek *et al* have implemented pressure sensing in a stack actuator for vibrotactile buttons [15, 16].

Self-sensing with DEAs has been studied [17], in particular by the Auckland group [18–21] (sensing commercialised with *StretchSense Ltd*). A DEA is effectively a compliant variable capacitor, and by sensing the capacitance the strain can be inferred.

Assaf *et al* [22] have demonstrated a DEA-actuated self-sensing whisker for tactile exploration.

Here we present the first example of two-way gesture-based tactile communication using a single DEA for both sensing and actuation.

2. THE TACTILE DISPLAY

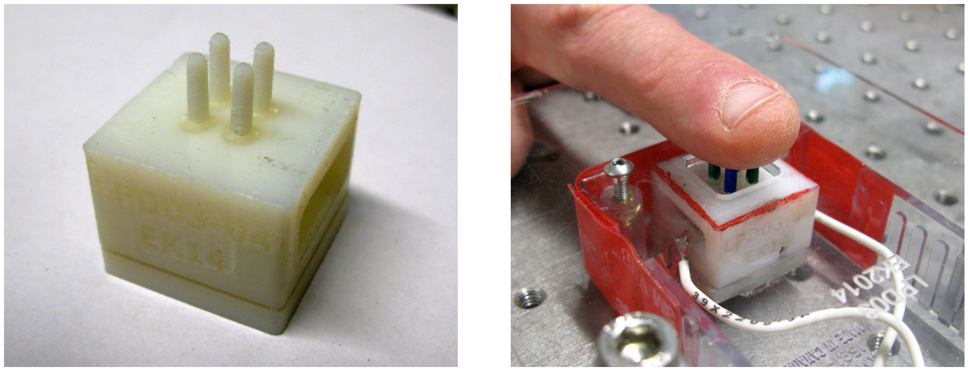
We have developed a Laterotactile Pin Display (LPD) inspired by the follicular structure of skin. The first prototype of the device has been presented previously [23]. In this paper we will therefore briefly discuss the LPD design and focus more on sensing capabilities.

Our mechanism is presented in Fig. 1. An array of pins are hinged at the surface ('skin') of the device, the user touches the top of the pins and a DEA membrane is attached to the bottom of the pins as indicated. Actuation of the DEA causes the pins to move laterally against the skin surface. Humans are highly sensitive to this laterotactile stimulation [24], which has previously been exploited in tactile displays [25]. One advantage of this follicular mechanism is that the high-voltage DEA can be inside the device, away from the user.

Here we consider a single tactile display element, comprised of four pins surrounding a DEA electrode. This means that the mechanism has 8 degrees of freedom (each pin can rotate about the x- and y-axes) and only one degree of actuation/sensing, so the complete state of the device cannot be inferred from sensing the strain of the DEA. The design could readily be scaled up to large arrays, but the single element is the fundamental building block and should be studied first.

The LPD was fabricated from rigid and compliant photocuring polymers using an Objet260 Connex 3D-printer (*Stratasys, Ltd.*), with the compliant material being used for flexural hinges as indicated in Fig. 1. We used a single-layer acrylic dielectric elastomer membrane (VHB 4905, *3M*), prestrained biaxially to 3.8 times the original length in each axis to give an estimated elastomer thickness of 31 μm. Electrodes were carbon grease (*MG Chemicals*), brushed on through a stencil.

The 3D-printed prototype is shown in Fig. 2a, and Fig. 2b shows a user touching the device.



(a) (b)

Figure 2: The 3D-printed LPD prototype.

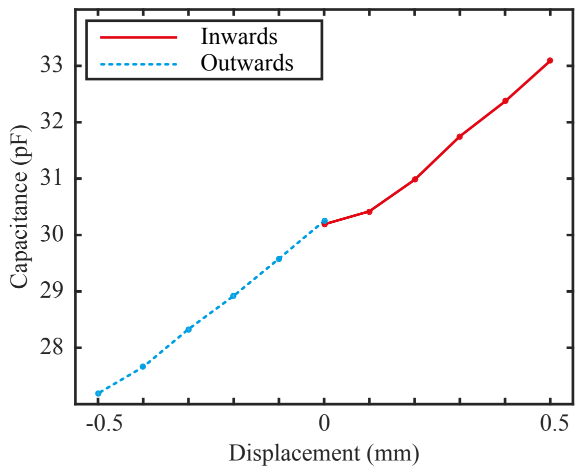


Figure 3: Change in capacitance with pins 1 and 2 being displaced in the positive (inwards) and negative (outwards) x-direction, pins 3 and 4 left unconstrained.

2.1 Sensing

The change in capacitance of the DEA is proportional to the square of the change in area [20]. As the device mechanism is underconstrained, it is impossible to infer the state of the device from the measured capacitance. The low capacitance of the device (approx. 30 pF at rest) makes it very sensitive to stray capacitance. This leads to relatively large fluctuations in the measured capacitance. This means that it is difficult to say anything meaningful from a single capacitance measurement. However, by looking for patterns in the temporal changes of the capacitance we can infer interaction gestures and filter out noise.

For capacitive measurements, we have used the AD7747 chip from *Analog Devices, Inc.*, interfaced to a PC with an Arduino Uno. This allows for sensing capacitance with a precision of ± 10 fF at a frequency of 46 Hz.

As a benchmark test, a linear stage was used to move the tops of pins 1 and 2 together, first in the positive x-direction (inwards) and then in the negative x-direction (outwards). The displacement and the resulting change in capacitance were measured. Pins 3 and 4 were left unconstrained. The results have been plotted in Fig. 3. There appears to be a linear relationship between displacement and capacitance that is consistent for inwards and outwards displacements. For larger strains, we would expect to be able to see the quadratic strain-capacitance relationship — in this case the relative strain is small so the relationship appears linear.

Due to the underconstrained mechanism, we cannot use this result to solve the inverse problem i.e. determining displacement from capacitance. That is; there is an infinite number of pin positions that map to a single

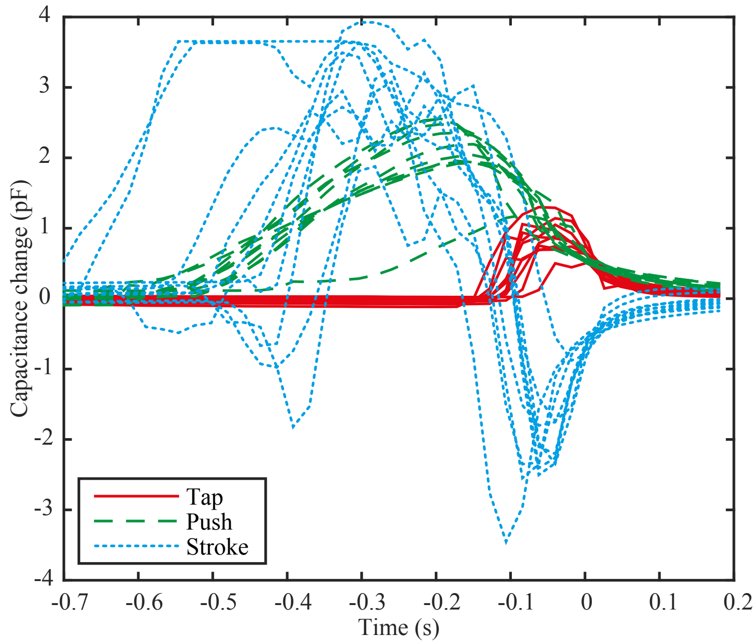


Figure 4: Temporal profiles for each of the gestures (*tap, push, stroke*). This shows that the capacitive measurement is sufficient to distinguish between the gestures.

capacitance value. Thus, this test serves to demonstrate that displacement of the pins results in a consistent and measurable change in the capacitance.

3. SENSING GESTURES

In order to extract meaning from the capacitive measurements, we need to look at the temporal patterns of the changes in capacitance. Gesture-based tactile interaction is frequently used in touch-screen devices.

Here we consider three gestures: *tap*, *push*, and *stroke*. *Tap* is briefly pressing down on the pins in the z-direction, *push* is pressing down on the pins in the z-direction but with greater force and for a longer duration, and *stroke* is dragging a finger laterally across the top of the pins (in the x- and y-directions).

A data set containing 10 temporal profiles of each gesture was collected, using the same setup for capacitive measurements described above. Slow changes in the capacitance with the device at rest, C_0, were observed due to stray capacitance, so for each profile we found the change in capacitance relative to C_0. Profiles were aligned temporally by aligning the end of the gesture — taken as the point where the capacitance came within 0.2 pF of C_0.

The resulting profiles are presented in Fig. 4. Clear differences can be seen between the different gestures. There is some spread in the profiles for each gesture, but the distinction between the different profiles is still clear.

For the *tap* and *push* gestures, the capacitance increases when the user pushes down on the pins. The *push* profiles show a greater change in capacitance for a longer duration, as the user pushes down on the pins harder and for a longer duration.

In the *stroke* pattern, the finger is moving across the top of the pins. High-frequency variations can be seen in the *stroke* profiles, likely from the stick-slip movement of the finger against the pins. Overall, it seems that the capacitance during a *stroke* event goes positive and then negative with respect to C_0. One explanation could be that for the first part of the gesture the user is pulling the pins on the far side of the device inwards leading to an increase in capacitance. For the final part of the gesture the near-side pins are pulled outwards, causing the capacitance to decrease.

Table 1: Performance of the classifier on the data from Fig. 4, down-sampled and quantised to mimic measurements from the SSU.

	Detected	Not detected	Misclassified
Tap	7	3	0
Push	9	1	0
Stroke	10	0	0

This result shows that we have the potential to detect the different tactile gestures with our follicular structure by measuring the capacitance of the single DEA.

4. TWO-WAY TACTILE COMMUNICATION

We now wish to combine the gesture recognition with tactile stimulation, to demonstrate two-way tactile communication.

In this experiment we have used the Self Sensing Unit (SSU) from *Auckland Biomimetics Laboratory*, controlled from MATLAB. This device allows for simultaneous sensing and actuation of DEAs. The resolution of the capacitive measurement is 1 pF, at 25 Hz, which means that for this application the change in capacitance from the different gestures will only give 1 or 2 bits of information. For this reason, we have implemented a simple rule-based classifier to detect the different gestures based on the results in Section 3 (Fig. 4). A higher-resolution capacitive measurement would allow for much more sophisticated detection and classification of gestures.

One fundamental example of two-way communication is *call-response*, where the user presents the device with an input and the device responds with a corresponding output. Here we have implemented a *call-response* demonstration, where the device detects the input gestures (*tap, push, stroke*) and responds to each one with a different tactile output.

The rule-based classifier for the gestures is described below using MATLAB syntax. The vector `c` is the capacitance relative to C_0, where `c(1)` is the most recent capacitive measurement, `c(2)` is the previous measurement etc.

```
if (all(c(1:2) == 0) && any(c(3:4) ~= 0) && all(x(7:8) == 0))
  tap();
elseif (all(c(1:2) == 0) && all(c(3:8) > 0) )
  push();
elseif (all(c(1:2) == 0) && min(c(3:5)) < 0 && max(c(4:10)) > 0)
  stroke();
end
```

This classifier was found to perform relatively well given the low information content of the input signal. After down-sampling and quantising the data set from Fig. 4 to mimic measurements from the SSU, 87 % of the gestures were detected and no gestures were misclassified. A breakdown of the classifier performance is presented in Table 1. With a higher-resolution capacitive measurement, a more sophisticated classifier could have been implemented.

For the *response* part, we defined the three patterns shown in Fig. 5 in such a way that they would be clearly detectable and also easy to differentiate between.

Combining the above, we have created an example demonstration of two-way tactile communication. The capacitance of the follicular device is monitored continuously for input gestures, and when gestures are detected the corresponding output patterns are displayed on the device, thus providing tactile communication. Fig. 6 shows an example of two-way tactile interaction. Coloured vertical lines show the points at which input gestures are detected. Both the sensing and actuation of the DEA can be seen in the capacitive measurements, as would be expected. In this implementation, the gesture detection was disabled during the presentation of output patterns.

This basic *call-response* demonstration shows two-way gesture-based tactile communication between the user and the device.

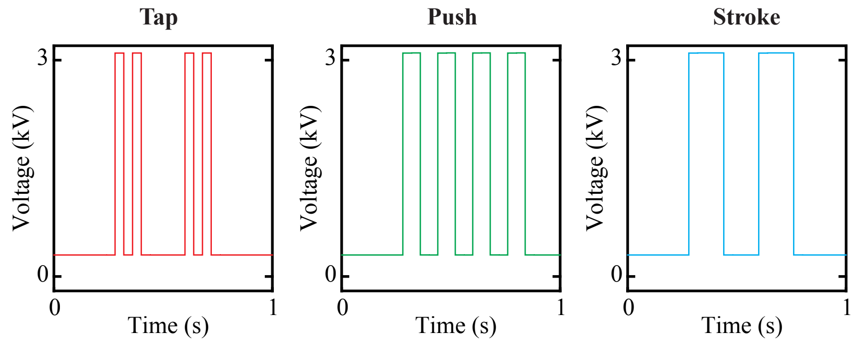


Figure 5: The output patterns used for the two-way tactile communication demo. For each detected input gesture, the device responds with the corresponding output pattern.

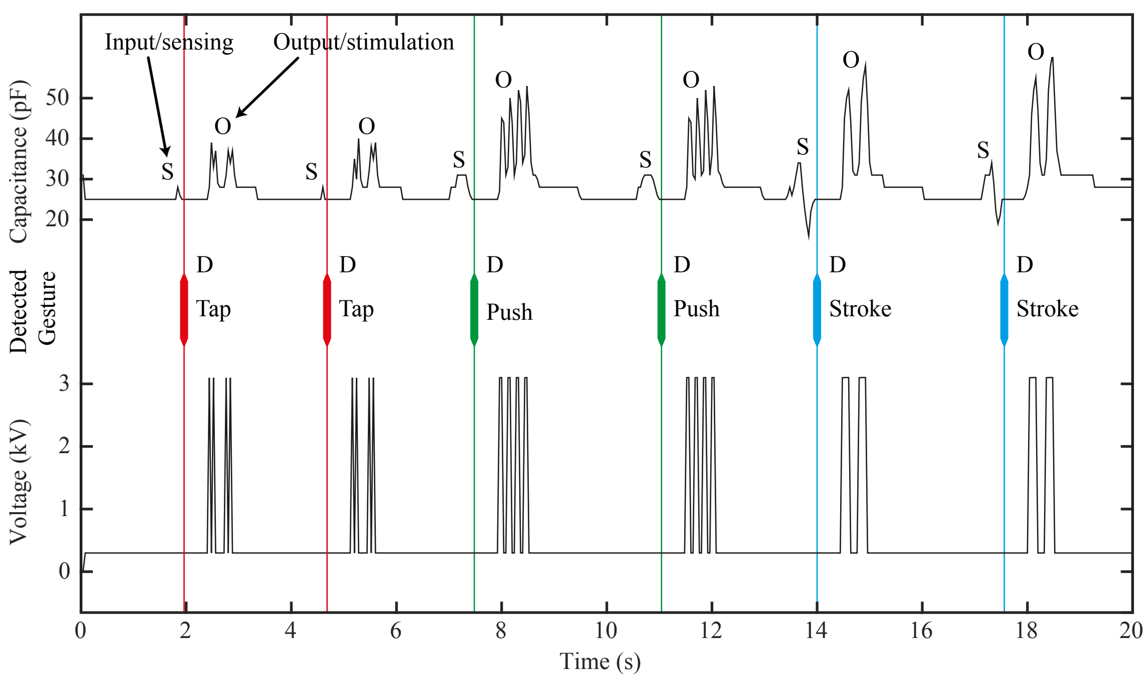


Figure 6: Output from the implemented *call-response* demonstration of two-way tactile communication, combining capacitive sensing (S), gesture detection (D) and tactile stimulation (O). The measured capacitance of the DEA is shown along the top, and the DEA driving voltage is shown along the bottom. Vertical lines show the points in time when gestures are detected, labelled and colour coded by gesture.

5. DISCUSSION

The capacitive measurements carried out here were relatively noisy, due to stray capacitance, and due to the underactuated follicular structure the state of the device could not be inferred from the measured capacitance. However, by analysing the temporal changes in the capacitance we could extract meaning from the capacitive sensing. In many robotic applications, in particular for human interaction, we are interested in the meaning of the sensory input rather than the absolute physical quantity it corresponds to. This is similar to how humans sense — we don't sense the absolute quantities of force or displacement but instead interpret the sensory input to give meaning.

Here we have considered a single tactile display element, but the design could be readily extended to a large sheet. This would allow for sophisticated sensing by combining capacitive measurements of multiple DEA elements. Local gestures could be sensed, as well as patterns moving across the sheet. A large sheet would also allow for complex tactile stimulation patterns to be presented. Here we used a prototype with a rigid frame, but a compliant frame would allow for a more natural compliant skin.

In a large array, the DEA elements would be coupled through the DEA membrane. Actuation of one element could be sensed in the neighbouring elements as the neighbouring elements would experience coupled strain. This could be exploited in a distributed 'cellular automata' skin structure, where the behaviour of each tactile display element is influenced by the external tactile input as well as the behaviour of the neighbouring elements.

6. CONCLUSION

In this paper we have demonstrated two-way tactile communication in a single follicular element capable of both sensing and actuation using a DEA. The low mechanical complexity of the mechanism, together with the combined DEA sensing and actuation, means that the design could readily be miniaturised and scaled up to a large tactile sheet.

The two-way tactile communication has been demonstrated through a simple *call-response* application, where *tap*, *push* and *stroke* gestures are detected using capacitive sensing and corresponding tactile responses are then presented to the user. The two-way tactile interaction could be used in a number of applications, including user-device communication and mediated user-user communication.

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