Bidirectional tactile display driven by electrostatic dielectric elastomer actuator

Hoa Phung, Canh Toan Nguyen, Hosang Jung, Tien Dat Nguyen and Hyouk Ryeol Choi

School of Mechanical Engineering, Sungkyunkwan University, Suwon, 24233, Republic of Korea
E-mail: phunghoa@skku.edu, toannguyen@me.skku.ac.kr, jhsx1004@skku.edu, tiendat@me.skku.ac.kr and choihyoukryeol@gmail.com

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Abstract
This paper presents a novel bidirectional tactile display by integrating an antagonistic dielectric elastomer actuator (DEA) with a V-shaped electrostatic actuator (EA), called electrostatic dielectric elastomer actuator (EDEA). Within a simple structure, this device can provide large out-of-plane vibration of the silicone-based DEA membrane. It is noted that, compared to the DEA alone, combining the soft DEA and electrostatic actuator significantly enhances the device performance by about 19.1% in terms of displacement and by about 14%–26% in terms of blocking force. We also analyze the constitutive DEA and EA models to predict the displacement and blocking force behaviors. The simulation results are consistent with the experimental results. The device is successfully fabricated by using 3D printing technology which simplifies the fabrication process and improves the scalability of the system. The tactile display can provide up to 680 μm of displacement and up to 185 mN of blocking force more than the human hand stimulus threshold (displacement/force). By controlling the input voltage and frequency, the device can generate different haptic feelings to the user.

Keywords: tactile display, dielectric elastomer actuator, bidirectional haptic, electrostatic actuator

(Some figures may appear in colour only in the online journal)

1. Introduction

Tactile displays are haptic devices that help people interact with environments via the sense of touch. Tactual sensations produced by mechanical, electrical, or thermal devices interact with human skin to provoke the brain’s tactile perception. Such sensations provide an essential touch signal as an alternative or supplement to two traditional senses of vision and hearing to improve data receiving capability. Hence, tactile devices have been widely investigated by researchers, and many new types of actuators have been used in the tactile display systems developed in these studies such as DC motors [1, 2], shape memory alloy (SMA) actuators [3–5], piezoelectric actuators [6], pneumatic pumps [7, 8], ultrasonic waves [9–11], linear electromagnetic actuators (LEA) [12, 13], electrorheological and magnetorheological fluid actuators [14–16], etc. Each of these actuators has advantages and disadvantages for tactile displays. For example, Boldea et al developed a haptic system using Rotary DC motors [2], and while it produced strong vibration that could be linearly controlled with the voltage or current, it had quite slow response time (tens of milliseconds) and the motor was relatively large. SMA tactile displays have also been investigated as they can provide large displacement and high force. However, SMA displays suffer from slow response time, high hysteresis effect, and large power consumption [5, 17]. Pneumatic actuators can provide fast response and, high force, but the system is quite complex and requires external
air pumps [7, 18]. In this paper, we introduce a new bidirectional tactile display actuator by integrating the dielectric elastomer actuator (DEA) and electrostatic actuator (EA).

Dielectric elastomers (DE), a class of electroactive polymers, are smart material that has attracted attention from many researchers due to their excellent material properties such as compliance, light weight, ease of fabrication, high elastic energy, large actuation strain (exceed 85% area strain with silicone elastomer), and high bandwidth (2000 Hz) [19, 20]. With these advantages, dielectric elastomer actuators (DEA) have been used in a wide range of applications in the field of soft robotics such as a directional navigation tail for a micro-air vehicle [23], and a soft fish robot [24]. To date, there have been many types of DEAs used for tactile displays [25–29]. However, the common weaknesses of DEAs are requiring high applied voltage (typical several kV) and low actuation stress caused by insufficient simulating force. Thus, multi-layering DEAs and hydrostatic coupling are often used to improve the actuation force [30–33].

Electrostatic actuators (EA) have been widely used in MEMS (micro-electro-mechanical systems) technology due to their advantages of low power consumption, high actuation speeds, large deflection, and high force [34–36]. Generally, the EA is based on attraction of two oppositely charged plates. Depending on different electrode configurations, various EA are possible. In this paper, two electrodes have a small V-shaped air gap between the elastomer and electrode. When the voltage applied to them causes the upper and lower layers to attract to each other, pushing the dielectric layer to the other side of the rigid electrode layer.

Taking inspiration from these technologies, we have recently developed a tactile display actuator which utilizes a combination of electrostatic attraction force and double conical dielectric elastomer actuators [37–39] to create large out-of-plane movement and fast vibration in a silicone-based elastomer membrane, as shown in figure 1. Vibration of the membrane can be used to stimulate the touch of a human finger. The device has two DEAs in an antagonistic configuration that mainly generate the displacement and force, as well as two EAs to enhance the whole actuator performance. By controlling the sequence of applying voltages, the prototype can produce excellent performance (large displacement and high force), which exceed the simulated displacement/force threshold for a human hand finger. We also evaluate each actuation state mode (active only each DEA, only each EA, and combined DEAs and EAs) to elucidate how EA contributes to the whole device performance. In addition, the fabrication of this device is extremely simple and highly scalable.

The rest of this paper is organized as follows: section 2 presents the DEA and electrostatic actuator working principle as well as the actuator design concept. Section 3 presents the actuator model analysis in order to elucidate the relationship between input voltage and blocking force. The simple fabrication processes are discussed in section 4. In section 5, the experiments performed to evaluate the actuator performance are presented. Finally, the discussion and conclusion are given in section 6.

2. Design and working principle of device

2.1. Working principle

The working principle of this device is a combination of a conventional DEA actuation and a V-shaped electrostatic mechanism. DEA consists of a thin dielectric elastomer membrane that is covered by compliant electrodes on both sides. When applying high voltage (typically several kV), it will generate Maxwell stress across the thickness membrane direction. Hence, as shown in figure 2(a), it will compress in the thickness direction and extend in the lateral direction. The DEA has shown that it can generate high strain over 200%. The Maxwell stress (P) is calculated as follows [40–42]:

\[ P = \varepsilon_0 \varepsilon_r E^2 = \varepsilon_0 \varepsilon_r \left(\frac{V}{t}\right)^2, \]

where \( \varepsilon_0 \) and \( \varepsilon_r \) are the free space permittivity (\( \varepsilon_0 = 8.85 \times 10^{12} \)) and relative permittivity of dielectric materials, respectively. \( E \) represents the electric field. \( V \) and \( t \) are the applied voltage and thickness of the dielectric elastomer layer, respectively.

The electrostatic attraction mechanism was first presented by Brandnebjerg and Gravesen in 1992 [43]. When high voltage is applied to the rigid electrode plate and the membrane is covered by electrodes on one side, the high electrostatic forces acting on the membrane surface will attract the membrane into the rigid electrode surface, as shown in figure 2(b). When the voltage is turned off, the membrane will return to its original position. In order to reduce the recovery time, the DE will be prestretched at the initial state. As shown in figure 3, the high voltage provided to the rigid electrode and the ground electrode of DEA will act like the electrostatic attraction mechanism.

2.2. Device design

Figure 3 shows the design of the electrostatic tactile display actuator, which has a circular shape with the overall dimensions of 36 mm × 36 mm × 30 mm (Length × Width × Height) (L × W × H). The device consists of four main parts, including two conical DEAs (DEA1, DEA2) and, two
rigid electrodes on the top and bottom used for electrostatic phenomena (EA1, EA2), while a touch spot is attached to the center of the disk where the finger is placed along with a 3D hollow cylinder to create the initial 1.1 prestrain of DEAs. The DEAs are made using Wacker Elastosil film then covered by compliant electrodes using carbon power material. The rigid electrode is made with silver paste and isolated by polyimide film to avoid short circuit with DEAs. The two DEAs are attached together with a 3D printing disk. A touch spot is then attached at the center of the membrane and the covering disk is finally placed on the top and bottom of the membrane for safety. Here, we attempt to minimize the central disk as much as possible in order to reduce the angle (α) of the rigid electrode and DEA electrode, to improve the electrostatic force [35].

Figure 4 illustrates how the displacement is generated, where it can be seen to have a bidirectional direction. The actuator is axi-symmetric structure. In the passive state, there is a plane symmetry of the balanced elastic forces within the two DEA membranes as well as an axial balance of normal forces between two DEA membranes acting on the 3D printing disk along the vertical direction; this is the antagonistic configuration. In the active state, when applying voltages on one DEA, it is expanded, and the other DEA will therefore reduce tension within the membrane. As a result, the 3D printing disk will pull to the inactive DEA. Simultaneously, high voltage is applied to the rigid electrode of the inactive DEA location. This will generate additional electrostatic force which will push the 3D printing disk stronger.

For example, figure 4(b) shows the voltages sequences applied to generate the bidirectional displacement. To move in the UP direction, voltages $V_1$ and $V_{e2}$ are ON while $V_2$ and $V_{e1}$ are OFF. Conversely, to move in the DOWN direction, voltages $V_2$ and $V_{e1}$ are ON while $V_1$ and $V_{e2}$ are OFF. By repeating these two sequences, the displacement of the device can be obtained as the total displacements of the UP and DOWN motion as follows:

$$D = D_{up} + D_{down},$$

where $D$ is the total vertical displacement of the touch spot or 3D printing disk and $D_{up}$ and $D_{down}$ are the displacements of each applied voltage set to create up or down movement, respectively.

3. Modeling of the tactile display

In this section, we analyze the blocking forces as the function of the actuator geometry and input high voltages. Two main forces acting on the central disk are the DEAs and EAs forces. Hence, the total force ($F_{total}$) is the sum of these forces as follows:

$$F_{total} = F_{DEAs} + F_{EAs},$$

where $F_{DEAs}$ and $F_{EAs}$ are the forces generated by the DEAs antagonistic actuation and electrostatic attraction, respectively.
In order to elucidate the contribution of each force to the whole actuator performance, we will study EAs and DEAs independently and compare the theoretical results with the experimental result. Table 1 shows the material characteristic parameters that we used in the modeling calculation.

### 3.1 Electrostatic actuator model

Due to the initial stretch ($\lambda_p = 1.1$), we assumed that the displacement caused by electrostatic attraction effect is small, therefore, we neglect the elastic force when analyzing the electrostatic force. We also simplify the electrostatic actuator model into $N$ parallel capacitors, as shown in Figure 5(b). Therefore, the total EA force $F_{EA}$ is the sum of $N$ electrostatic forces $F_i$, as shown in equation (4)

$$ F_{EA} = \sum_{i=1}^{N} F_i. \quad (4) $$

Now, as shown in Figure 5(a), the model becomes a pair of electrodes isolated by polyimide material and an air gap. Each layer has each permittivity ($\varepsilon_1$, $\varepsilon_2$), electrical conductivity ($\sigma_1$, $\sigma_2$), thickness ($d_1$, $d_2$) and electrical field ($E_1$, $E_2$). This model is similar to the Johnson–Rahbek model, so the gradual increase in the electrostatic force ($F_i$) of a $i$th capacitor under an applied voltage can be calculated as follows (44):

$$ F_i = \frac{1}{2} \varepsilon_2 A_i E_{2i}(t)^2, \quad (5) $$

where $A_i$ is the area of the $i$th ground electrode of the $i$th capacitor and $E_{2i}$ denotes the electrical field of the air gap calculated at the $i$th capacitor. According to equation (5), the electrostatic force is a function of the electrical field $E_{2i}$ because $A_i$ and $\varepsilon_2$ are constant. The area $A_i$ is expressed as:

$$ A_i = \pi \times (r_i + r_{i+1}) \times h_0 \times \cos(\alpha), \quad (6) $$

where $r_i$ and $r_{i+1}$ are the radii of the circular capacitor $i$th and $i+1$th, respectively. $h_0 = h/N$ is the average height of each capacitor. $\alpha = \tan(h/(R – r))$ is the angle of EA.

Next, we must determine the electrical field $E_{2i}$. According to a previous study [45], the applied voltage is divided into two: DC and AC voltages. However, here we only consider the AC case, because we control the actuator with frequency to generate the vibration. The condition of applied AC frequency is $\omega >> \frac{\sigma d_1 + \sigma d_0}{\varepsilon d_2 + \varepsilon d_0}$ (rad s$^{-1}$). By replacing the material parameters in Table 1, $\frac{\varepsilon d_2 + \varepsilon d_0}{\varepsilon d_2 + \varepsilon d_0}$ is much smaller than currently used $\omega = 0.63 \div 1$ 884.96 (rad s$^{-1}$) (or $= 0.1 \div 300$ (Hz)). With $V = V_0 + V_0 \sin(\omega t)\sin\omega t$, the electrical field $E_{2i}$ becomes:

$$ E_{2i}(t) = \frac{\varepsilon_1}{\varepsilon_1 d_2 + \varepsilon_2 d_1} (V_0 + V_0 \sin\omega t), \quad (7) $$

where $t_{2j} = i \times h_0$ is the height of the $i$th air gap. By substituting equation (7) into equation (5), the electrostatic force

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**Table 1.** Material characteristic parameters used in simulation and experiment.

| Properties                          | Wacker film | Polyimide film |
|-------------------------------------|-------------|----------------|
| Thickness ($\mu$m)                  | 50          | 50             |
| Dielectric constant ($F/m$)         | 2.8         | 3.4            |
| Electric conductivity ($S/m$)       | 0.001 56    | 6e$^{-16}$     |
| Breakdown strength ($MV/m$)         | 100         | 118            |
| Young’s modulus (MPa)               | 0.5         | 2500           |
can be obtained as follows:

\[ F_i = \frac{1}{2} \varepsilon_2 A_i E_2(t)^2 = \frac{1}{2} \varepsilon_2 A_i \frac{\varepsilon_1^2}{(\varepsilon_1 d_2 + \varepsilon_2 d_1)^2} (V_0 + V_0 \sin \omega t)^2 \]

(8)

Figure 6(a) shows the result of EA2 force with different numbers of divided capacitors \((N)\), starting at 1 and ending at 5000. If \(N\) is small (<1000), the maximum simulated EA force will be less accurate. When \(N \geq 2000\), the resulting force will be almost constant at 32 mN. Therefore, \(N = 2000\) is chosen to simulate the electrostatic force versus input AC voltage. Figure 6(b) illustrates the EA force behaviors depending on the applied AC voltage. The force is proportional squared with voltage. When the voltage reaches its maximum at 4.5 kV, the maximum force of 32 mN will be recorded. It is noted that the simulation results of EA1 and EA2 are the same absolute amplitudes. But EA1 force has a negative sign; in contrast, EA2 force has a positive sign.

Figure 6. Result of modeling electroadhesion force, (a) relationship between number of divided EA \((N)\) and maximum simulated EA force with input voltage of 4500 V, (b) simulated EA force is a function of AC input voltage.
The maximum simulated EA1 forces and experiment results at different input voltages (0.5–4.5 kV) are compared in figure 7. The simulated force is slightly higher than experiment force, with respective values of −32 and −19 mN. The reason for these differences is that, in the simulation, we neglect the masses of DEA, central disk, and touch spot. However, there is still reasonable agreement between the two.

3.2. Dielectric elastomer actuator model

At the passive state, the DEAs are prestretched with 10% area strain ($\lambda_p = 1.1$). Thus, elastic energy is stored inside of DEs. This means that, when voltage is applied to the DEA, there are two forces of elastic force ($F_{\text{elastic}}$) and electrostatic force ($F_{\text{electrostatic}}$), that can be described as follows:

$$F_{DEA} = F_{\text{elastic}} + F_{\text{electrostatic}}.$$  

The potential energy function is a common approach method used to compute the hyperelastic material model. From the Gent model, the strain energy density function of DE can be described by [46]:

$$W(\lambda_1, \lambda_2, \lambda_3) = -\frac{\mu J}{2} \ln \left(1 - \frac{\lambda_1^2 + \lambda_2^2 + \lambda_3^2}{J^2}\right),$$  

where $\mu$ and $J$ are Gent model parameters and $\lambda_1$, $\lambda_2$, and $\lambda_3$ are the prestretch ratios along direction of 1, 2, and 3 respectively, as referring to the longitudinal, latitudinal and transverse directions of the DE membrane as shown in figure 5(b).

DE is hyperelastic material with nonlinear deformation behavior. To simplify the model calculation, here, we assume that the latitudinal stretch $\lambda_2$ is always constant and equal to initial area stretch $\lambda_2 = \lambda_p$ regardless of Z-axis displacement of the central disk.

DE is an incompressible material, then $\lambda_1 \times \lambda_2 \times \lambda_3 = 1$. Call $z$ is the vertical displacement as defined in figure 5. The longitudinal stretches ($\lambda_{1,\text{DEA1}}$, $\lambda_{1,\text{DEA2}}$) and transverse stretches ($\lambda_{2,\text{DEA1}}$, $\lambda_{2,\text{DEA2}}$) of the DEAs are computed as follows:

$$\begin{align*}
\lambda_{1,\text{DEA1}} &= \lambda_p \sqrt{\frac{(R-r)^2 + (h-z)^2}{R-r}}, \\
\lambda_{1,\text{DEA2}} &= \lambda_p \sqrt{\frac{(R-r)^2 + (h+z)^2}{R-r}}, \\
\lambda_{2,\text{DEA1}} &= \frac{1}{\lambda_{\text{DEA1}}} \sqrt{\frac{(R-r)^2 + (h-z)^2}{R-r}}, \\
\lambda_{2,\text{DEA2}} &= \frac{1}{\lambda_{\text{DEA1}}} \sqrt{\frac{(R-r)^2 + (h+z)^2}{R-r}}.
\end{align*}$$

Now, the elastic strain energy generated by prestretching a DEA becomes:

$$U_{\text{elastic}} = N_{\text{layer}} \times \text{vol} \times W(\lambda_1, \lambda_2, \lambda_3),$$  

where $\text{vol} = \pi (R^2 - r^2) \frac{d_0}{\lambda_p}$ is the volume of each DEA after prestretching and $d_0$ is the initial DE thickness. $N_{\text{layer}} = 1$ is the number of DE films layer on one side. Replacing equation (10) into elastic strain energy equation (13) yields:

$$U_{\text{elastic}} = \text{vol} \times -\frac{\mu J}{2} \ln \left(1 - \frac{\lambda_1^2 + \lambda_2^2 + \lambda_3^2}{J^2}\right).$$  

Next, the electrostatic strain energy of the DEA when high voltage $V$ is obtained can be determined by [47]:

$$U_{\text{electrostatic}} = -N_{\text{layer}} \frac{1}{2} CV^2 = -N_{\text{layer}} \frac{1}{2} \varepsilon_0 \varepsilon_r \frac{A}{(d_0/\lambda_p)} V^2,$$

where $C = \varepsilon_0 \varepsilon_r \frac{A}{(d_0/\lambda_p)}$ is the capacitance of the DE film, $N_{\text{layer}} = 1$. $A$ denotes the area of electrode. While applying voltage, the central disk will move vertically at displacement $z$, and the electrode area also changes according this displacement as follows:

$$\begin{align*}
A_{\text{DEA1}} &= \pi (R + r) \sqrt{(R-r)^2 + (h-z)^2}, \\
A_{\text{DEA2}} &= \pi (R + r) \sqrt{(R-r)^2 + (h+z)^2}.
\end{align*}$$

Finally, the total energy can be obtained as the sum of the elastic and electrostatic energies as a function of voltage $V$ and displacement $z$ as follows:

$$U_{\text{total}} = U_{\text{elastic1}}(z) + U_{\text{electrostatic1}}(z, V1) + U_{\text{elastic2}}(z) + U_{\text{electrostatic2}}(z, V2).$$

The DEAs are in antagonistic actuation, when $V_1 > 0$, $V_2 = 0$ and vice versa $V_2 > 0$, $V_1 = 0$. The displacement of the central disk along the $z$ direction can be determined by solving the total energy function presented in equation (17) at the local minimum of the total energy $U_{\text{total}}$ [23]:

$$\begin{align*}
\frac{\partial U}{\partial z} &= 0, \\
\frac{\partial^2 U}{\partial z^2} &> 0.
\end{align*}$$

Finally, the blocking force ($F_{DEA}(z, V)$) is the derivative of the total energy $U_{\text{total}}$ along with the displacement $z$ when $V_1 > 0$, $V_2 = 0$:

$$F_{DEA}(z, V) = \frac{\partial U_{\text{elastic1}}(z)}{\partial z} + \frac{\partial U_{\text{elastic2}}(z)}{\partial z} + \frac{\partial U_{\text{electrostatic1}}(z, V1)}{\partial z} + \frac{\partial U_{\text{electrostatic2}}(z, V2)}{\partial z}.$$  

Figure 7 shows the simulated $F_{DEA2}$ results as well as the experiment results. They share the same tendency and quite good accordance. At the peak input voltage 4.5 kV, the maximum simulated DEA2 force is about −200 mN, while the experimental force is about −160 mN. As depicted in equation (3), the total simulated force is the sum of EA and DEA, which is about −230 mN at 4.5 kV. The DEA mainly provides 86% of the total generated force while the EA force contributes 14%.
4. Fabrication processes

The fabrication processes of the proposed device are very simple, as shown in Figure 8. Most of the parts (top cover, bottom cover, hollow cylinder frames, central disk, and touch spot) are 3D printed using a STRATASYS machine with material named VeroWhite Plus RGD835. First, the top and bottom covers are brushed with silver paste (ELCOAT P-100) electrode, a highly conductive material, and isolated by polyimide (KAPTON-100B) with a thickness of 50 μm. Secondly, to make the DEA, the dielectric elastomer named Wacker ELASTOSIL film with a thickness of 50 μm is used in a circular shape without prestretching. This DE has high-precision film (±5% of thickness) and is durable. Next, two circular masks are cut using a laser cutter machine. These masks are tightly attached to both sides of the DE film and brushed with compliant electrode (carbon black power, Ketjen-Black-600JD). We also use the conductive threads to wire out.

After preparing the top and bottom covers and the two actuators, the actuators are adhered on the hollow cylinder, then the 3D central disk is attached into the centers of two actuators in opposing directions to create prestrain 10%. A touch spot is then attached to the central disk as shown in Figure 8(d). The Kapton adhesive tape is cut in a hollow circular shape and attached to the DEAs using 3D printing parts. Figure 8(e) shows the completed tactile display prototype with the overall dimensions of 36 mm × 36 mm × 30 mm (L × W × H).

5. Experimental results

5.1. Experimental setup

In order to measure the displacements, blocking forces, and frequency responses, an experimental setup is needed, as shown in Figure 9. In this setup, the laser sensor (Keyence LK-G150-0.1 μm in resolution) is used to measure the displacement when applying different voltages and frequencies. Figure 9(b) illustrates the setup used to measure the blocking forces, including the push–pull gauge (Aikoh RZ-1) used with the minimum measurable force of 1 mN. The sine wave high voltages are provided by Trex-10/10B controlled by the functional generators (Tektronix TDS3014B). To fully measure the functions of the prototype, a sequence sine wave voltage was generated as shown in Figure 9(c).

5.2. Results

After fabricating the tactile display as shown in Figure 1, we perform several experiments aiming to investigate

![Figure 8. Fabrication processes of the tactile display actuator, (a) 3D printed top and bottom covers, (b) DEA, (c) separate parts before assembly, (d) assembled bottom cover with two DEAs and touch spot, completed prototype with dimensions of 36 mm × 36 mm × 30 mm (L × W × H).](image)

![Figure 9. Experimental setup for (a) displacement, (b) blocking force, (c) output driving high voltage from Trex-10/10B applying to the full EDEA.](image)
displacement responses with different input voltages, frequency responses, and blocking force responses.

5.2.1. Displacement responses. The maximum voltage that DEA can endure is 5 kV but for safety, we only applied up to 4.5 kV starting from 0.5 kV and increasing in steps of 0.5 kV to measure the displacement. As shown in figure 10, six actuator states are measured lower DEA only (DEA1), lower DEA with upper electrostatic actuator (DEA1 and EA2), upper DEA only (DEA2), upper DEA with lower electrostatic actuator (DEA2 and EA1), upper and lower DEAs only (DEA1 and DEA2), and full actuator.

The DEA1 only produces positive displacement with a maximum of 260 μm at a peak voltage of 4.5 kV. When applying to both DEA1 and EA2, the displacement is 361 μm, representing an increase of about 27.8% compared with the activation DEA1 alone. Similarly, the DEA2 only produces negative displacement with a maximum of −320 μm, and increases up to −380 μm if combining with EA1, representing an increasing of about 15.8% of displacement. The full actuator generates a maximum displacement of 680 μm, 19.1% larger than that of only upper-lower DEAs (DEA1 and DEA2) produces (550 μm). This proves that the use of an additional electrostatic actuator amplifies the displacement.

5.2.2. Frequency responses. In this test, the voltage is fixed at 4.5 kV, the frequency swipes from 1 to 300 Hz, and the displacement is recorded. Similarly, for displacement vs voltage responses, six actuation states were measured, as shown in figure 11. Generally, when increasing the frequency, the displacement will be decreased. It is because of the relaxation times of dielectric material is not fast enough to follow the frequency change of the applied electrical field. The maximum displacement (several hundred μm) is generated at 0.1 Hz, then gradually decreases when higher frequencies are applied. At low frequency (<7 Hz), the EAs play an important role in contributing to the displacement of the whole system. When the applied frequency is between 7 and 50 Hz, the effect of the EAs to the whole system will be smaller and it will be saturated if the frequency exceeds 50 Hz.

5.2.3. Blocking force responses. For the next test investigating blocking force responses, we fix the frequency at 0.1 Hz and change the applied voltage from 0 to 4.5 kV. Figure 12 shows the blocking force of the touch spot. The DEA1 only generates positive force with a maximum of 85 mN at a peak voltage of 4.5 kV, and when activating both DEA1 and EA2, the force increases up to 115 mN, which is about 26% greater. Similarly, the DEA2 only produces negative force with a maximum of −155 mN. Further, when combining with EA1, representing an increase of about −180 mN. This proves that the combination of EAs and DEAs increases the overall performance of the system. It should be noted that the threshold force for simulating a
finger is about 50 mN \([48, 49]\); thus, our actuator can provide many different feelings to users.

5.2.4. Durability test. For testing the actuator durability, we did a cyclic performance with the same previous fabricated actuator after 5 months. We applied voltage of 4.5 kV and frequency of 1 Hz for about 20 min. Figure 13 shows the displacement about 700–800 \(\mu\)m, it is almost the same performance with previous test. That is because of the outstanding durability of the Wacker silicone that used in this research.

6. Conclusions

In this paper, we propose a new kind of tactile display combining a dielectric elastomer actuator and an electrostatic actuator. The device is compact and involves simple fabrication processes. We analyze the theoretical models of the EA and DEA to predict the force behavior with different input AC voltages. The simulation results, EA1 force of \(-32\) mN and DEA2 force of \(-200\) mN, is slightly higher then experimental results, \(-19\) mN and \(-160\) mN, respectively. But they still shares the same tendency.

Six actuation states depending on the applied voltage sequences, lower DEA only (DEA1), lower DEA with upper electrostatic actuator (DEA1 and EA2), upper DEA only (DEA2), upper DEA with lower electrostatic actuator (DEA2 and EA1), upper and lower DEAs only (DEA1 and DEA2), and full actuator, are experimentally evaluated in term of displacement, frequency, and blocking force responses.

By using an additional EA mechanism, the tactile display can create more displacement and force, and thus improve the overall performance of the actuator (about 19.1% in terms of displacement and by about 14%–26% in terms of blocking force. As the result, the actuator produces 680 \(\mu\)m of displacement and 280 mN of blocking force). These exceed the human threshold (100 \(\mu\)m, 50 mN) for simulating a finger. Therefore, the device can create different stimuli to the user.

Comparing with the other well-known developed multi-stacked DEAs \([33, 50]\), they can produce up to 9 \(N\) of blocking force with the small actuator size of 16 \(\times\) 16 \(\times\) 20 mm\(^3\). To obtain this high force, the actuator needs to have hundreds of DE layers. If only one layer is burned, whole actuator is broken. The fabrication process is complicated to make uniform thickness of each layer, and it is not stable method for making tactile display. Here, our actuator only uses 2 DE pre-stretched membranes, and the other parts are 3D printed. Therefore, if the DEA is broken, we easily replaces a new one. It is to be noted that the DEA requires high voltage. In addition, safety is the first priority in the actuator design. In our mechanism, the high voltage is totally isolated with the touch-spot, where the user is touching.

The proposed tactile display works at a wide range of frequencies (0.1–300 Hz), and provides soft feeling to the users. Hence, it is a good candidate for haptic feedback system. In the near future, this device may be used in a wearable type to be used in other domain of applications such as virtual reality etc. For further research, an optimization of the initial prestretch of DEA and the initial angle of electrostatic mechanism structure are needed to improve the force and displacement.

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ORCID iDs

Hyouk Ryeol Choi @ https://orcid.org/0000-0003-2902-7453

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