IEICE TRANS. ELECTRON., VOL.E104–C, NO.2 FEBRUARY 2021

INVITED PAPER *Special Section on Electronic Displays*

Tactile Touch Display Using Segmented-Electrode Array with Tactile Strength Stabilization

Hiroshi HAGA[†,††a)], **Takuya ASAI**[†], **Shin TAKEUCHI**[†], **Harue SASAKI**[†], **Hirotsugu YAMAMOTO**[††], ***and* Koji SHIGEMURA**[†], ***Nonmembers***

SUMMARY We developed an 8.4-inch electrostatic-tactile touch display using a segmented-electrode array (30 × 20) as both tactile pixels and touch sensors. Each pixel can be excited independently so that the electrostatic-tactile touch display allows presenting real localized tactile textures in any shape. A driving scheme in which the tactile strength is independent of the grounding state of the human body by employing two-phased actuation was also proposed and demonstrated. Furthermore, tactile crosstalk was investigated to find it was due to the voltage fluctuation in the human body and it was diminished by applying the aforementioned driving scheme.

key words: *electrostatic tactile display, electrostatic force, touch sensor, human body, tactile crosstalk, localized tactile texture*

1. Introduction

The success of multi-touch touchscreens has enabled us to interact intuitively with displays through touch surfaces. We have been interacting with displays via not only the visual sensory channel but also the tactile one. This meets the user demand for rich tactile feedback.

Three types of tactile displays can be combined with visual displays: (I) one in which the touch surface vibrates with mechanical actuators such as coil-based actuators [1] or piezoelectric devices [2], (II) an electrostatic tactile display in which the electrode is located under an insulator layer [3], [4], and (III) an electro-tactile display that directly activates sensory nerves via an electrical current [5]. In type (II), the skin is attracted by electrostatic force when a high AC voltage is applied to the electrode. When a finger slides across the surface of the display, a tactile sensation is produced upon detection of the horizontal deformation of the skin produced by dynamic friction variation transformed from electrostatic force variation. This effect is known as "electrovibration." [6]

We previously reported an electrostatic tactile display that produces stimulation in regions to accommodating multi-touch or multi-person tactile interactions [10], [11]. A 240-Hz electrostatic force was generated by the beat phenomenon in a region where X electrodes excited by 1000-Hz cross Y electrodes excited by 1240 Hz, creating a localized tactile sensation from the entire surface. This localization technique takes advantage of the property of human mechanoreceptors, which have high sensitivity around 200 Hz and low sensitivity over 1000 Hz. Because a tactile sensation can be localized on the touch surface, each finger should sense its own stimulus. This feature also allows multiple users to feel the texture of an image that they touch individually. Moreover, the tactile sensation is consistent with the visual image, even if the user slides his/her finger quickly, while it is inconsistent due to time lag between touch being detected and actuators being activated in the conventional system, which does not feature stimulus localization. On the basis of this electrostatic tactile display, we developed a capacitive touchscreen-integrated electrostatic tactile display with localized sensation [12]. Every electrode on the panel is driven for both the tactile presentation and the touch sensor by using the combination of time and space multiplexing control. Furthermore, we have proposed a capacitive touchscreen-integrated electrostatic tactile display with localized sensation using a segmented-electrode array [13], which will be elaborated in this paper.

Electrovibration was discovered in 1953 by accident. Mallinckrodt et al. [7] reported that if a dry finger is moved gently over a metal surface covered with a thin insulating layer and the metal is excited with a 110-V AC power line, the surface has a characteristic rubbery feeling. The first attempt at using electrovibration for tactile applications was reported by Strong in 1970 [8]. He buried an array of metal pins into a plastic body having flat heads insulated with a thin layer of dielectric. A combination of an electrostatic tactile display and a visual display was reported by Bau et al. in 2010 [3]. Nakamura et al. proposed a transparent electrostatic tactile display that included a film slider in 2016 [9]. They described a multi-user capability and capacitive position-sensing capability in their paper. The prototype consisted of an indium tin oxide (ITO) electrode sheet arranged on a monitor and multiple contact pads for electrostatic adhesion. By applying low-frequency haptic voltage and high-frequency sensing voltage to each pad, on which the user puts his/her finger, the system created passive haptic feedback as well as position sensing using the same components. Applications were limited because each pad was tethered for applying voltages. The combination of an electrostatic tactile display and a projected capacitive touchscreen was reported by Kim et al. [14]. They stacked

Manuscript received March 20, 2020.
Manuscript revised June 2, 2020.
Manuscript publicized July 22, 2020.

[†]The authors are with Tianma Japan, Ltd., Kawasaki-shi, 212–0058 Japan.
[††]The authors are with Utsunomiya University, Utsunomiya-shi, 312–0904 Japan.
a) E-mail: h-haga@tianma-jp.com

DOI: 10.1587/transele.2020DII0005

a conductive layer for the electrostatic tactile display on a projected capacitive touchscreen. To form the electrostatic capacitance between the electrode of the capacitive touchscreen and a finger even through the conductive layer, a high impedance conductive layer of 10^6 Ω/square and more was used. The localization of the tactile sensation was not addressed in [14]. Ilkhani et al. proposed a tactile display that creates multi-touch tactile feedback using electrostatic attraction. The method relies on applying high-voltage AC signals of 250 Hz on certain orthogonal electrode lines, resulting in perceivable changes in friction at the intersection points [15]. However, this method is limited in terms of the low contrast of the tactile sensation. The reason is that the driving voltage must be set so that the friction force exceeds the detection threshold of fingers at the intersection points, while the friction force does not exceed the detection threshold along the electrodes other than the points. This method relies on the difference in friction forces to produce a localized sensation. In comparison, the method that we reported [10], [11] uses not only the difference in friction forces but also the difference in friction frequency that affects the sensitivity of our mechanoreceptors, which have the potential to increase the contrast of the tactile sensation.

The first issue underlying the related work described earlier is the shape of the geometrical figure of the localized texture. The degree of freedom of the shape is limited because the tactile panel comprises X and Y electrodes and because the localized texture is presented around the crosses of the excited X and Y electrodes. This scheme can present, for example, the shape of a rectangle of localized texture but cannot present the shape of a triangle, a doughnut, or a zig-zag path.

The second issue is that the tactile strength fluctuates depending on the grounding state of the human body. Actually, [3] uses a ground bracelet to present stable and strong tactile strength to users. [3] mentions that although our bodies provide a natural link to the ground, creating a direct ground connection significantly increased the intensity of the tactile sensation. We have also experienced that the tactile strength fluctuates depending on the grounding state of the human body.

The third issue is tactile crosstalk, which was reported in our previous work [12]. [12] mentions that in the case of touching and sliding with the index finger and the middle finger of the same hand simultaneously, a finger perceived a dependent tactile sensation. When the index finger was in the target region to present tactile stimulus and the middle finger was grounded region, the middle finger perceived electrovibration slightly in spite of touching the grounded region. This artifact hinders multi-finger tactile interactions.

In this paper, we describe two schemes for the tactile touch display. First, we describe an electrostatic tactile touch panel using a segmented-electrode array. Our electrostatic tactile panel features 8.4 inches in diagonal size and 600 (30 × 20) electrodes, each of which can be controlled independently. The diagonal size and the number of electrodes are the world's largest ever. Second, we elaborate on a driving scheme for tactile strength stabilization in which the tactile strength is independent of the grounding state of the human body. This paper discusses the performance with a special paid on the tactile crosstalk issue.

2. Electrostatic Tactile Touch Panel

The tactile sensation of the electrostatic tactile display is generated by providing vibration or shear force to a user's finger by controlling friction using electrostatic adhesion. This mechanism is associated with the electrostatic force between a finger and the electrode and formulated using the parallel-plate capacitor model. Figure 1 shows the electrical and kinetic models. The electrostatic force between two objects having a voltage difference—a finger and the electrode in the aforementioned case—can be simply estimated as

$$F_e = \frac{1}{2}\varepsilon S_e \left(\frac{V_e}{d}\right)^2, \tag{1}$$

where F_e is the electrostatic attraction force, ε is the dielectric constant, S_e is the contact area, V_e is the voltage difference, and d is the gap between the objects. While a person explores the touch surface, his/her finger motion converts the electrostatic force into friction as

$$F_f = \mu(F_e + F_a), \tag{2}$$

where F_f is the friction force, μ is the friction coefficient, and F_a is the sum of the other normal forces (e.g., contact force exerted by the finger). Therefore, controlling the voltage difference can modulate friction force [9].

The electrode in our tactile touch panel is also used for the touch sensor. These two functions are time-multiplexed. Touch is detected by measuring the capacitance C between a finger and the electrode. A current to voltage (I/V) converter was used for the capacitance sensing, as shown in Fig. 2. It senses the electric capacitance connected to the inverting input node of the operational amplifier. The amplitude of the output voltage V_2 increases in accordance with the increase in the capacitance [12].

Our electrostatic tactile touch panel using a segmented-electrode array is illustrated in Fig. 3. This tactile touch panel consists of a glass substrate, multiple electrodes segmented in a square shape made of an ITO, signal lines connected to an electrode one by one, a first insulator layer that

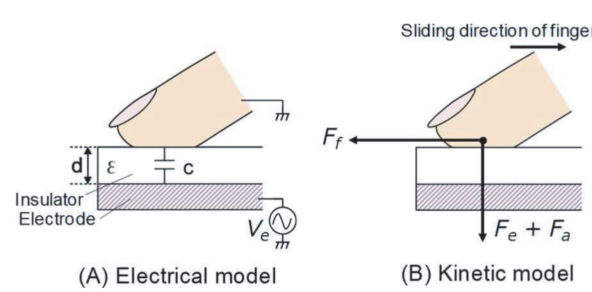


Fig. 1 Origin of tactile sensation of electrostatic tactile display.

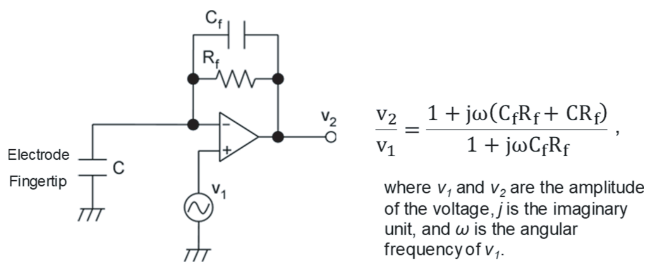


Fig. 2 Touch sensing using a single electrode. The amplitude of the output voltage v_2 increases in accordance with the increase in the capacitance C.

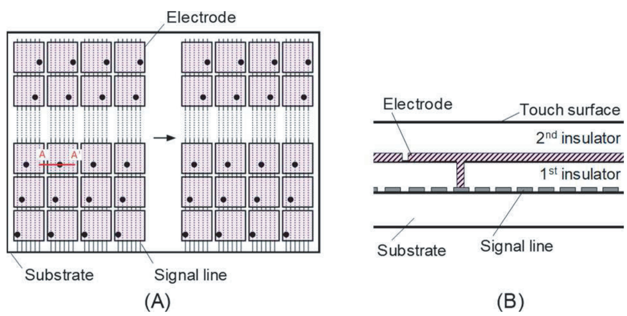


Fig. 3 (A) Electrostatic tactile touch panel using a segmented-electrode array. (B) Cross sectional view of A-A'.

separates electrodes from signal lines, and a second insulator layer that covers the electrodes.

3. Driving Scheme for Tactile Strength Stabilization

We have experienced that the tactile strength fluctuates depending on the grounding state of the human body. Bau used a ground bracelet to present strong tactile strength to users [3]. Stable tactile strength without a ground bracelet is desired. In this section, we first present the reason for tactile strength fluctuating in [3] in 3.1. Then, we describe our proposed driving scheme for tactile strength stabilization in 3.2. After that, our experimental results demonstrating its effect are shown in 4 and 5.

3.1 Analysis of Fluctuations in Tactile Strength

Two additional elements to the model are needed to analyze the fluctuations in tactile strength. One is the impedance Z between the fingertip to ground, and the other is fingertip voltage V_f. The model, which includes these two elements, is shown in Fig. 4. This model has a single electrode, which is the same structure that Bau [3] used. Note that the ground connected to the impedance Z in Fig. 4 is AC ground. That is, the ground is the same as a circuit element that passes AC current at the frequency of a signal voltage V_e. For example, a metal plate having a capacitive coupling to the earth has the possibility of being ground.

In the case of the model in Fig. 4, electrostatic attraction force F_e is obtained by modifying the Eq. (1) as

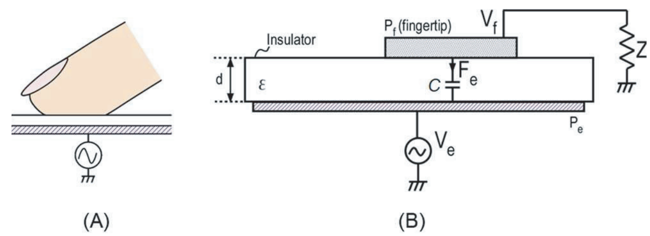


Fig. 4 Single electrode structure. (A) Geometrical structure. (B) Electrical model.

$$F_e = \frac{1}{2}\varepsilon S_e\left(\frac{V_e - V_f}{d}\right)^2, \tag{3}$$

where ε is the dielectric constant, S_e is the contact area, V_e is the voltage of the electrode P_e, V_f is the voltage of the fingertip P_f, and d is the gap between the electrode and the fingertip. Equation (3) shows that the electrostatic attraction force is the function of the fingertip voltage V_f. The fingertip voltage V_f is obtained from the circuit equation of Fig. 4 (B) as

$$V_f = \frac{j\omega Z}{\frac{d}{\varepsilon S_e} + j\omega Z} V_e, \tag{4}$$

where Z is the impedance between the fingertip to ground, ω is the angular frequency of the voltage of the electrode P_e, and j is the imaginary unit. Thus, electrostatic attraction force F_e depends on the impedance between the fingertip to ground (Z).

Appropriate substitutions helped our understanding. Thus, we investigated two extreme conditions. The first condition was a Z of zero. In this case, V_f was fixed to 0 volts. The electrostatic attraction force F_e was

$$F_e = \frac{1}{2}\varepsilon S_e\left(\frac{V_e}{d}\right)^2. \tag{5}$$

The second condition was a Z of infinity. In this case, V_f was the same as the voltage of the electrode V_e. The electrostatic attraction force was

$$F_e = 0. \tag{6}$$

(5) and (6) explain the reason for Bau [3] needing a ground bracelet.

3.2 Driving Scheme for Tactile Strength Stabilization

Figure 5 shows the model of the multiple electrode structure. We divided the electrodes into two groups. The electrodes in the first group were supplied V_{e1}, and the electrodes in the second group were supplied V_{e2}. If the finger-contact area overwrapped two electrodes as shown in Fig. 5 (B), the finger P_f faced two electrodes driven by the voltage V_{e1} and V_{e2} each.

We set the voltages of V_{e1} and V_{e2} as sinusoidal waveforms of the same frequency with the phase difference Φ. Specifically, each waveform was $V_0 \sin(\omega t)$ for V_{e1} and

$V_0 \sin(\omega t + \Phi)$ for V_{e2}, where ω was an angular frequency expressed as the product of 2π and frequency. The electrostatic attraction force F_{total} between the finger and the two-faced electrodes is a simple sum of two electrostatic attraction forces from each electrode F_{e1} and F_{e2}.

In the case that Z is zero, F_{total} is

$$F_{total} = \frac{1}{4}\varepsilon S_e\left(\frac{V_0}{d}\right)^2\left\{2 + \sqrt{2(1+\cos 2\Phi)}\,\sin(2\omega t + \alpha)\right\}, \tag{7}$$

where S_e is the area of one electrode opposite the finger and α is a constant.

In the case that Z is infinity, F_{total} is

$$F_{total} = \frac{1}{4}\varepsilon S_e\left(\frac{V_0}{d}\right)^2\left\{1-\cos\Phi-(1-\cos\Phi)\sin(2\omega t+\beta)\right\}, \tag{8}$$

where β is a constant.

These Eqs. (7) (8) have vibration terms and constant terms. The terms of interest are the vibration terms because human mechanoreceptors have high sensitivity around 200 Hz of electrostatic force [11] and because the constant electrostatic force does not present tactile sensation. Note that, as with other reports and our previous work, the user feels an electrostatic tactile sensation derived from the vibration term only while the user is sliding the finger on the surface and doesn't feel the sensation without any explorative movement.

The vibration term in (7) is

$$\frac{1}{4}\varepsilon S_e\left(\frac{V_0}{d}\right)^2\sqrt{2(1+\cos 2\Phi)}\,\sin(2\omega t + \alpha), \tag{9}$$

and the vibration term in (8) is

$$\frac{1}{4}\varepsilon S_e\left(\frac{V_0}{d}\right)^2(\cos\Phi - 1)\sin(2\omega t + \beta). \tag{10}$$

The coefficients of vibration terms change as Φ changes. Figure 6 shows coefficients in the cases of both $Z = 0$ and $Z = \infty$. In the case $Z = 0$, the absolute value of the coefficient becomes zero when the phase difference is 90 degrees and becomes the maximum when the phase difference is 0 and 180 degrees. In the case $Z = \infty$, the absolute value of the coefficient becomes zero when the phase difference is 0 degrees and monotonically increases as the phase difference increases up to 180 degrees. We can find two points in which the absolute value of the coefficient does not depend on Z; these are when the phase differences are 70.5 and 180 degrees. On the basis of this figure, we suggest that the tactile strength stable against the grounding state of the human body and the tactile strength is strong when the phase difference is 180 degrees.

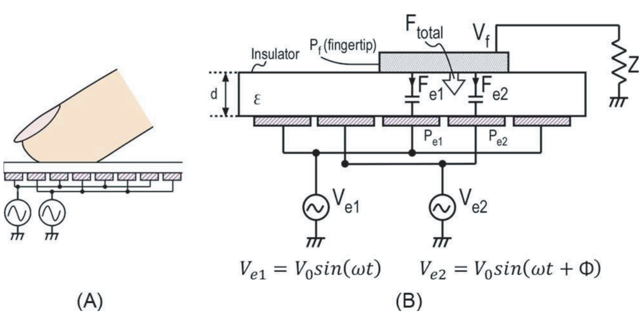


Fig. 5 Multiple electrode structure. (A) Geometrical structure. (B) Electrical model.

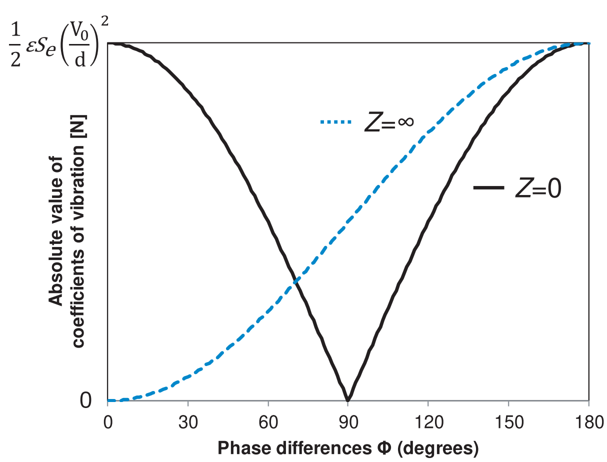


Fig. 6 Calculated coefficients of vibration.

4. Perception Test for Tactile Strength Stabilization

We measured the detection threshold voltage instead of measuring the vibration term of the electrostatic attraction force because measuring the electrostatic attraction force directly was difficult. The detection threshold voltage can be an indicator of the vibration term of the electrostatic attraction force because the frequency of the electrostatic attraction force is affected by neither Φ nor the grounding state of the human body in our model. Thus, we can assume that the Φ presenting small detection threshold voltage presents a large vibration term of electrostatic attraction force under the same driving voltage (V_0). We used the tactile touch panel shown in Fig. 3, where the size of each electrode was 5.1 × 5.1 mm. Each of the electrodes supplied with voltage V_{e1} and V_{e2} were arranged in a checkered pattern in a plane view (see Fig. 7). We chose 100 Hz as the frequency of the sine wave for V_{e1} and V_{e2} (200 Hz as the frequency of

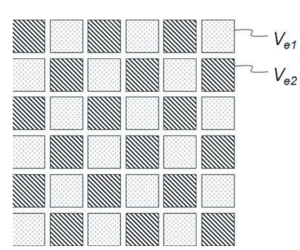
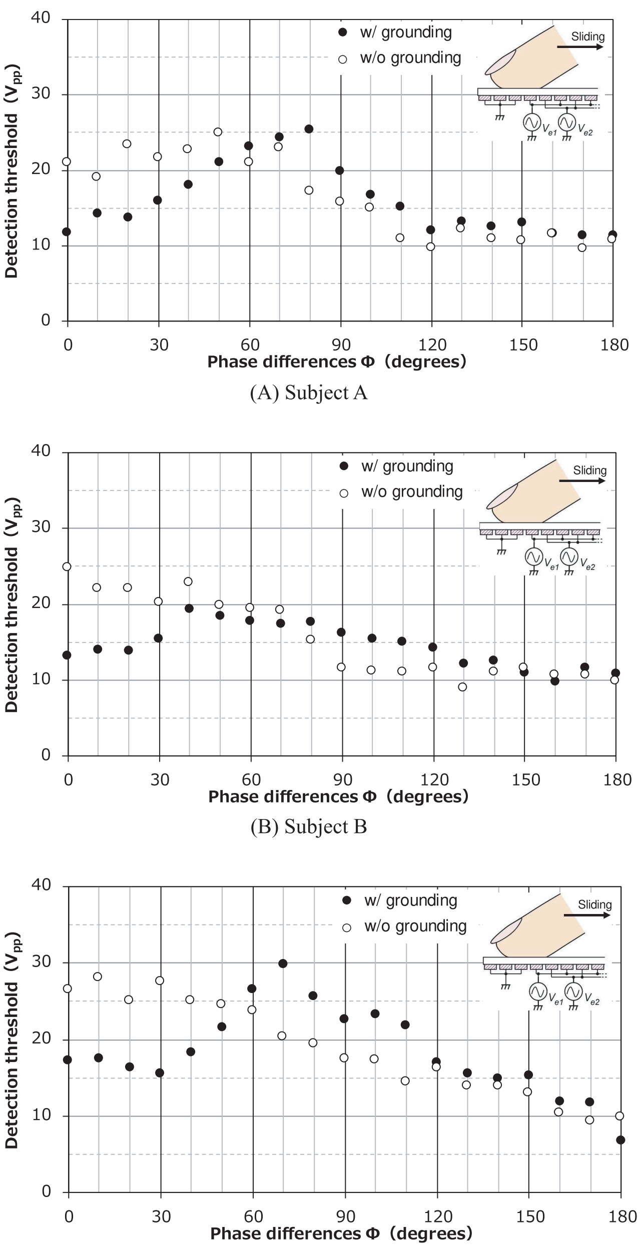


Fig. 7 Driving scheme for measuring detection threshold voltage.

the electrostatic attraction force) so that our tactile sensory system became highly sensitive. We measured the detection threshold voltages by changing two parameters: Phase differences Φ and the grounding state of the human body (W/ or W/O grounding).

Three subjects participated in this test (two males and one female, ages: 28-54).

Figure 8 (A), (B) and (C) shows the measured detection threshold voltage for the phase differences for each subject. By comparing three figures, we can see individual differences, while we can see that, at the phase difference of 180°, the detection threshold voltage is stable against the grounding state of the human body and the detection threshold voltage is small. These results demonstrate that the vibration term of the electrostatic attraction force was large and stable when Φ was 180°. We utilized this driving condition in our tactile touch display as the driving scheme for tactile strength stabilization.



(A) Subject A

(B) Subject B

(C) Subject C

Fig. 8 Measured detection threshold voltage vs. phase differences.

5. Tactile Crosstalk

We studied whether or not our tactile touch display in this work provides independent stimulations to multiple fingers simultaneously.

5.1 Tactile Crosstalk in Previous Work

We have experienced the tactile crosstalk or the tactile artifact in our previous electrostatic tactile display and we reported that it is due to the voltage fluctuation in the human body as a reasonable explanation [12]. The electrostatic tactile display in our previous work has multiple X and multiple Y electrodes as shown in Fig. 9. These electrodes are covered with a thin insulator layer. To present localized sensation in the target region (ex. the region in the dotted square in the figure), X electrodes under the region (X_2 and X_3) is excited by the AC voltage signal of 1000 Hz and Y electrodes under the region (Y_4 and Y_5) is excited by the AC voltage signal of 1240 Hz. When the finger opposes to both excited X electrode and excited Y electrode, the electrostatic attractive force of 240 Hz occurs between the finger and the electrodes by beat phenomena. Since the frequency of 240 Hz is highly sensitive for our mechanoreceptors, it can present localized sensation in the target region.

5.2 Perception Tests of Tactile Crosstalk

Figure 10 (A) shows the types of regions of our tactile touch display in previous work. There are four types of regions (rgnT, rgnX, rgnY, and rgnG) on the panel depended on the

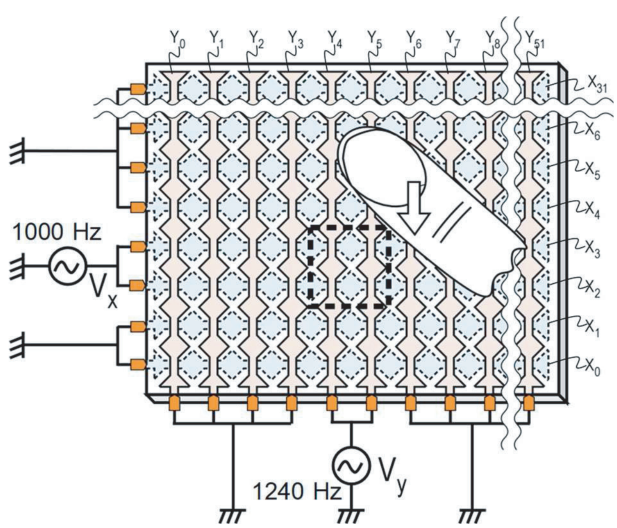


Fig. 9 Electrostatic tactile display in previous work [10].

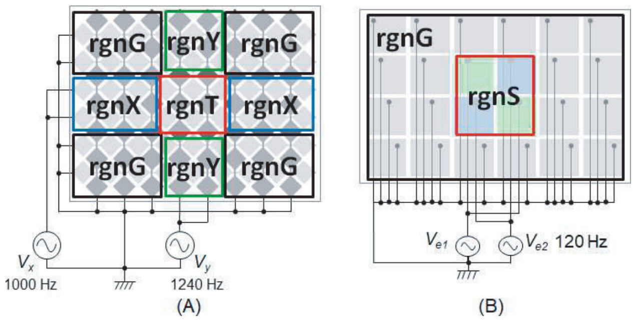


Fig. 10 (A) Tactile touch display in our previous work. (B) Tactile touch display in this work.

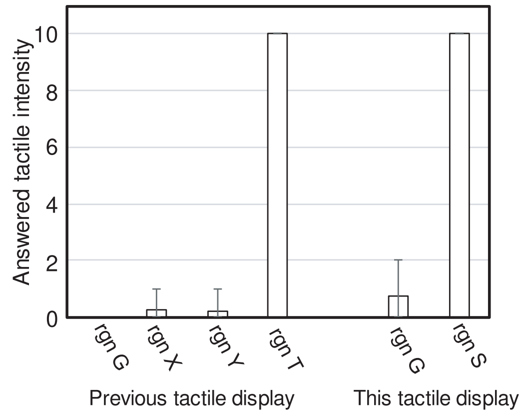


Fig. 11 Rated tactile intensity with one finger.

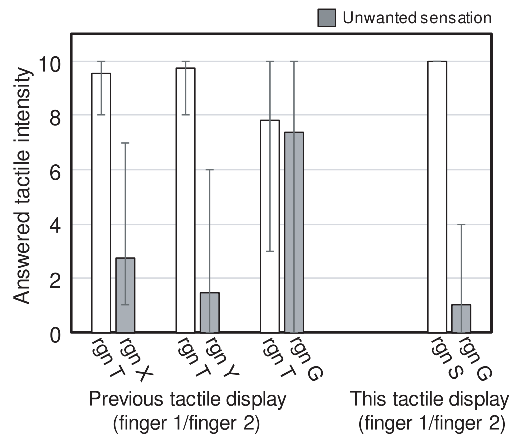


Fig. 12 Rated tactile intensity with two fingers.

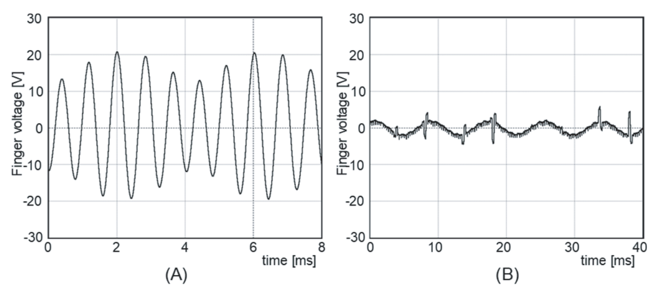


Fig. 13 (A) Measured finger voltage opposing to the grounded electrodes using previous tactile display. (B) Measured finger voltage opposing to the grounded electrodes using the tactile display in this work.

driving voltage state. RgnT was the target region to present tactile sensation, where both X and Y electrodes were excited and where the vibration of the electrostatic attraction force of 240 Hz occurred by beat phenomena. RgnX was the region where only X electrodes were excited by 1000 Hz, which was too high frequency to be perceived as tactile sensation. RgnY was the region where only Y electrodes were excited by 1240 Hz, which was also too high frequency be perceived as tactile sensation. RgnG was the region where both X and Y electrodes were connected to the ground. Figure 10 (B) shows the tactile touch display in this work. Two types of regions were evident (rgnS and rgnG): rgnS was the target region to present tactile sensation, where electrodes were excited and vibration of the electrostatic attraction force of 240 Hz occurred, and rgnG was the region where electrodes were connected to the ground.

The tactile intensity was rated by participants when touching and sliding each of these regions in two conditions, with one finger and with two. In the condition of one finger, the participant explored each of these regions. In the condition of two fingers, the participant explored the target region with one finger and explored the non-target region with another finger simultaneously. Eleven participants were tested (nine males and two females, ages: 25-60). The reference tactile intensity when exploring the target region with one finger was set to 10 and when exploring the region rgnG in previous work with one finger was set to 0, then the tactile intensity of each finger was rated by participants. Figures 11 and 12 show the experimental results. Figure 11 shows the average tactile intensity and the maximum/minimum intensity in each region when the participant explored with one finger. In the non-target region, the tactile intensity was almost zero compared with the tactile intensity in the target region. With the one-finger operation, both the previous tactile display and the tactile display in this work demonstrated localized tactile sensation. Figure 12 shows the average tactile intensity and the maximum/minimum intensity perceived by each finger in each region when two fingers explored the target region and the non-target region simultaneously. In the previous tactile display, tactile crosstalk happened in each case, and this was an unwanted tactile sensation occurring in a finger exploring a non-target region. In the tactile display in this work, the tactile intensity in the non-target region was almost zero, as in the case of one finger. The results show that the issue of tactile cross-talk disappeared in this work.

5.3 Finger Voltage Fluctuation

We measured finger voltage fluctuation to confirm that the tactile crosstalk is due to the voltage fluctuation in the human body. Figure 13 shows measured finger voltages. Figure 13 (A) was obtained by using previous tactile display when two fingers explored the target region (rgnT) and the non-target region (rgnG) each simultaneously.

Figure 13 (A) shows the voltage of the finger touching rgnG measured on the finger skin between the 1st and 2nd joints. The voltage fluctuation in which the beat frequency of around 240 Hz was obtained. This voltage fluctuation is induced by another finger touching rgnT. Since the finger voltage that touches rgnG fluctuates, the finger senses tactile sensation even the electrodes opposing the finger were connected to the ground.

Figure 13 (B) was obtained by using the tactile display in this work when two fingers explored the target region (rgnS) and the non-target region (rgnG) each simultaneously. The voltage was also measured at the finger skin touching rgnG. The measured voltage fluctuation was smaller than the voltage fluctuation in Fig. 13 (A). It is because the finger touching rgnS was opposed to electrodes driven by reverse polarity voltages ($\Phi = 180°$) by our tactile strength stabilization scheme.

These measured finger voltage fluctuations support that the tactile crosstalk is due to the finger voltage fluctuation induced by the finger touching the target region.

6. Visuo-Tactile Touch Display

Figure 14 shows the schematic of our visuo-tactile touch display using the tactile touch display of this work, which has 600 (30×20) electrodes. Each electrode is a 5.1 mm square and is laid on the substrate with a gap of 50 μm between adjacent electrodes. The tactile touch display can generate real localized tactile textures at arbitrary positions in any shape by supplying signal voltage to intended signal lines. All of the electrodes are used both as a tactile display and a touch sensor. For the electrodes to have two functions, every signal line is connected to one of the tactile driver and the touchscreen controller via a single-pole double-throw (SPDT) switch in accordance with the control signal of the system controller. Each SPDT switch can be controlled independently. At a certain time, only a very small number of electrodes are connected to the touchscreen controller and the rest (most of 600 electrodes) are connected to the tactile driver. The switch controller scans all electrodes to be connected to the touchscreen controller by controlling SPDTs sequentially. The scan rate and the report rate of touch detection were designed at 100 Hz, which is the common rate of commercial products.

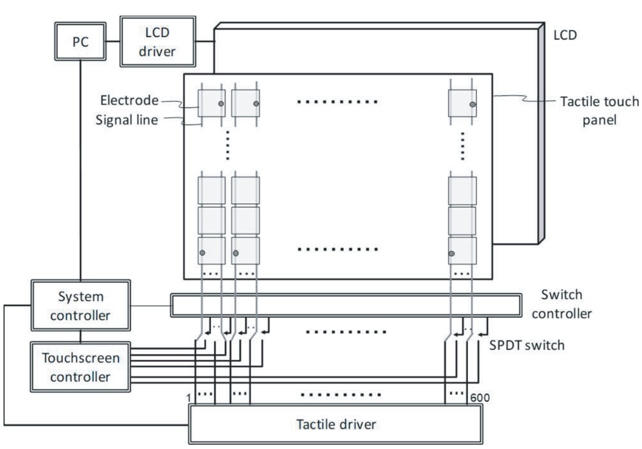


Fig. 14 Schematic of visuo-tactile touch display.

The tactile driver supplies voltage signals for tactile sensations. It has 600 output terminals as shown in Fig. 15. Each output terminal was connected to the SPDT switches in Fig. 14 one by one. The tactile driver outputs AC voltage signals (V_{e1} or V_{e2}) on the terminals corresponding to the target regions to present tactile sensations and outputs the ground voltage on the terminals corresponding to the non-target regions. Figure 17 (B) shows an example of the electrode status driven by the tactile driver. The tactile driver has the capability of 100 Hz of frame rate, thus the shape of the geometrical figure of the localized texture can be changed at 100 Hz. It is high enough for tactile interactions.

The tactile touch panel is optically bonded on the LCD. Users can enjoy both visual information from the LCD and tactile information from the tactile touch display at the same time. Table 1 summarizes the specifications.

We created demos using visual and tactile interactions.

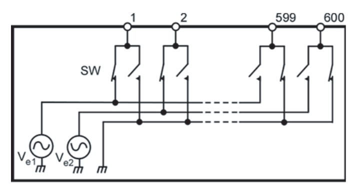


Fig. 15 Schematic of tactile driver.

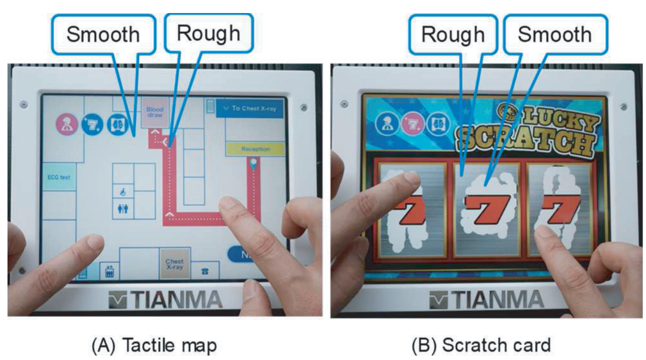


Fig. 16 Photograph of visuo-tactile touch display.

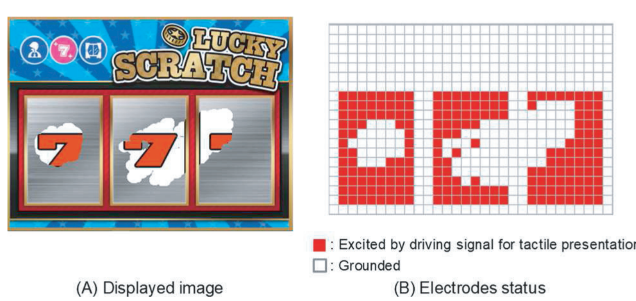
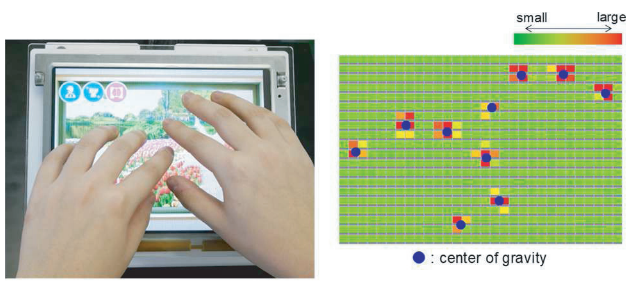


Fig. 17 Correspondence between displayed image and excited electrodes.

Table 1 Specifications of 8.4-inch visuo-tactile touch display.

Visual display (LCD)	Size (inches)	8.4"
	Active area (mm)	170.4 × 127.8
	Resolution (pixels)	800 × 600
	Luminance (cd/m^2)	800
Tactile touch display	Number of electrodes	30 × 20
	Electrode unit size (mm)	5.1 × 5.1
	Touch point	10-point touch
	Report rate of touch detection (Hz)	100
	Tactile display type	Friction control
	Tactile signal frequency (Hz)	120



(A) Photograph interacting with 10 fingers (B) Heat map of touch detection

Fig. 18 Touch detection of the tactile touch display.

In the first demo, a tactile map in a medical facility shows us the route to the destination visually and tactilely (see Fig. 16 (A)). The signal voltages for the tactile sensation are supplied only to the electrodes on the route image. We can distinguish complex routes and the other places tactilely. In the second demo (see Fig. 16 (B)), when a user scratches his/her finger on the touch surface, he/she can feel a rough texture sensation on silver covered parts, then see the hidden image after it is peeled off, and after that feel a smooth texture on the hidden image. In both of these demos, users can feel the stable tactile sensation as intended with the right hand, the left hand, and both hands. Figure 17 (A) is a screenshot of the demo image, and Fig. 17 (B) shows the electrodes excited for tactile presentation. As Fig. 17 shows, the tactile touch display generates real localized tactile textures at arbitrary positions in any shape corresponding to the visual object. We also demonstrated the function of the touch sensor. Figure 18 (A) shows a photograph interacting with ten fingers. The 10-point touch detection was demonstrated as shown in Fig. 18 (B).

7. Conclusions

We proposed a segmented-electrode structure tactile touch panel and demonstrated that it can generate free-shaped localized tactile sensations at arbitrary positions. We also proposed a driving scheme for tactile strength stabilization in which the tactile strength is independent of the grounding state of the human body, resulting in it being free from a ground bracelet. This scheme also solved the issue of tactile crosstalk due to the fluctuation in the human body potential. Therefore, this work enhances the degree of freedom in designing new user experiences of human-display interactions.

Acknowledgments

We wish to express our appreciation to the members of Akita plant in Tianma Japan, Ltd. for fabricating the tactile touch panel and to the members of Tianma Micro-electronics Co. for their continued guidance and encouragement.

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Hiroshi Haga received his B.E. degree in image science and technology from Chiba University, Japan, in 1994. He then joined NEC Corporation, where he was engaged in the research and development of polycrystalline silicon TFT circuits and their application devices including image sensors, LCDs, and OLEDs. In 2011 he joined NLT Technologies, Ltd., which has been renamed Tianma Japan, Ltd., where he has been developing human-display interaction technologies including tactile and touch technologies. He is a Senior Manager at Tianma Japan, Ltd. He is also a doctoral course student of Utsunomiya University, Japan. He is the General Secretary of the Workshop on Touch Panels and Input Technologies in the International Display Workshops (IDW). He received the Young Researcher's Award from the Institute of Electronics, Information and Communication Engineers (IEICE) in 1999 and the Best Paper Award from IDW in 2017. Mr. Haga is a member and the program committee of the Society for Information Display.

Takuya Asai received his BSc and MS degrees in Materials Science from Tohoku University, in 1999 and 2001, respectively. He joined NEC Corp. in 2001, where he was engaged in the research and development of display devices, such as LCDs, 3-D displays, and e-Paper displays. In 2011, he joined NLT Technologies, Ltd., which has been renamed Tianma Japan, Ltd., and he is now the Assistant Manager of Research & Development Department.

Shin Takeuchi received his B.E. and M.E. degrees in Instrumentation Engineering from Keio University, in 1990 and 1992, respectively. He joined Fuji Xerox Corp. in 1992, where he was engaged in the research and development of human interface technology, such as voice input, haptic mouse, and digital pen. In 2018, he joined Tianma Japan, Ltd., and he is now the Research Expert of Research & Development Department.

Harue Sasaki received her B.S. and M.S. degrees from Ochaomizu University, Japan, in 2014 and 2016, respectively. In 2016, she joined NLT Technologies, Ltd., which has been renamed Tianma Japan, Ltd., where she has been developing human-display interaction technologies.

Hirotsugu Yamamoto was born in Wakayama, Japan, in 1971. He received his B.E., M.E., and Ph.D. degrees from the University of Tokyo. From 1996 to 2008, he was an assistant professor at Tokushima University. From 2009 to 2014, he was an associate professor at Tokushima University. From 2014 to 2019, he was an associate professor at Utsunomiya University. Since Sept. 2019, he has been a full professor at Utsunomiya University. His recent work activities have included aerial display, digital signage by use of high-speed LED panels, and information photonics. Dr. Yamamoto was a recipient of Young Scientist Award for the Presentation of an Excellent Paper, The Japan Society of Applied Physics, Outstanding Poster Paper Award at IDW'03, IDW'04, IDW'07, IDW'08, IDW'09, IDW'10, IDW'11, IDW'12, IDW'13, IMID2014, IDW'14, IMID2015, IDW'15, IMID2016, IDW'16, IDW'17, IMID2018, and IDW'18, Best Paper Award at DHIP2011, IDW'11, and IDW'15, Best 3D Demonstration Award at Stereoscopic Displays and Applications 2012, the Gen-Nai Grand Prize from the Ozaki Foundation of Japan, and SPIE the Fumio Okano Best 3D Paper.

Koji Shigemura received his B.E. and M.E. degrees in Precision Mechanics from the University of Tokushima, Japan, in 1990 and 1992, respectively. He joined NEC Corp. in 1992. He has been engaged in the research and development of FPD devices and systems including OLEDs, LCDs, e-Paper, and 3-D display. In 2011, he joined NLT Technologies, Ltd., which has been renamed Tianma Japan, Ltd., where he has continued to research FPD and related emerging technology. He is now the General Manager of Department Division in Tianma Japan, Ltd.