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Basic Characteristics of Printable Large-Area Electrostatic Tactile Display*

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Abstract— **We have developed a large printable electrostatic tactile display based on electrostatic tactile and paper electronics technology. In this display, it is possible to impart tactile sensation to a specific part of a symbol alone by printing a color ink for that symbol on the electrode. The use of a paper medium makes the display easy to enlarge and develop at low cost and it can be rolled up, miniaturized and carried easily. We studied the possibility of uniform tactile presentation over a large area in this display, and the effect of the color ink layer on the perceived intensity. As a result, no large voltage drop due to enlargement of the display was observed. No difference in perceived intensity due to the amount of color ink used was found. The results thus confirmed that it is possible to print vivid graphics using large amounts of ink and that the proposed display can be used as a poster.**

I. Introduction

Recent interest in virtual reality has spurred major interest in tactile displays that feed tactile sensations back to provide user experiences. Tactile sensation presentation methods can generally be divided roughly into three types: wearable-type, gripping-type, and stationary-type methods, which all depend on the features of the device to be used. However, existing devices that can be classified into these types have various disadvantages that are also dependent on the device features. First, wearable-type devices can present deep immersive feelings by interlocking with the other senses and can also present tactile sensations to the whole body; however, the attachment and detachment complexity and high equipment costs can be regarded as demerits [1] [2]. In gripping-type devices, the experiencer's movement is limited by the need to grasp the devices [3]. Additionally, in stationary-type devices, higher quality electrostatic tactile sensations are provided by arrays of electrodes and 3D tactile sensation are produced by combining electrostatic tactile sensation and mechanical vibrations, but these devices are mostly small at present and thus can only present tactile sensation to the user's fingertip [4] [5]. Therefore, it is necessary to develop a new display that can overcome these drawbacks to present a sensation of touch over the entire palm without restricting the user's movement using a simple and low-cost approach.

We focused our attention on the paper electronics and electrostatic tactile sensation technologies, which provide excellent device simplicity when compared with other tactile presentation methods. Paper electronics technology uses conductive ink printed on paper to form electrodes. Several studies using paper electronics technology have been conducted to date. Li et al. developed a touch sensor [6] that was created by printing conductive ink alone. In addition, Nakahara et al. developed a flexible motor using a circuit based on conductive ink [7]. Their research was effectively a way of mimicking the flexibility of animals by printing conductive inks on paper and causing flexible motion in the paper itself by thermal change. Kato et al. developed a wearable-type tactile display by combining paper electronics technology with electrical stimulation and electrostatic tactile sensation [8]. As another example of a flexible tactile display using electrostatic tactile sensation, Ishizuka et al. developed a small sheet-type electrovibration-based tactile display that consisted of poly(3,4-ethylenedioxythiophene) polystyrene sulfonate conductive layers and an insulation layer of polydimethylsiloxane. This tactile display was thin and flexible enough to be attached to various surfaces [9]. These studies showed that it is possible to develop an electrostatic touch display using electrodes fabricated by printing conductive ink.

In addition, several studies on large-area electrostatic tactile displays have also been conducted. Bau et al. developed transparent large-sized touch displays that can impart tactile sensation to various surfaces, including touch displays and furniture [10]. They also developed an electrostatic tactile presentation device for 3D objects [11]. However, these displays require complex apparatus and the resulting cost is high.

Therefore, we aimed to develop a large-area tactile sensation technology for use on areas such as the palm, the arm and the face using a simple and low-cost approach; we then aimed to develop a new poster-type electrostatic tactile display using both conductive ink and color printing ink. In this display, by printing color inks for the patterns on the electrode, tactile sense presentation can be matched to specific parts of symbols. In addition, it is possible to present various sensations by varying the applied AC voltage waveform.

In this paper, we clarify whether uniform tactile sensation can be presented over a large area and consider the influence of the color printed ink layer on the perception intensity. We then verify the usefulness of this display.

II. Proposed Tactile Display

The configuration used for the printable electrostatic tactile display developed in this work is shown in Fig. 1. In this display, we printed silver nano-ink [12] (Mitsubishi Paper Mills Co., Ltd., Tokyo, Japan; NBSIJ-MU 01, volume resistivity of $<1.0\times10^{10-5}$ Ω·cm) on a white polyethylene terephthalate (PET) film that is used as a mount for electrode preparation. This silver nano-ink is used as an electrode. On the upper layer of the electrode, a white background ink that

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acts as a base for printing of symbols was coated over the entire surface. This white background ink covers the electrode pattern. Then, on the upper surface of this layer, the actual color printing ink that forms the main body of the pattern was printed. By matching and overlapping the shape of the electrode with that of the pattern, it is possible to impart tactile sensation to a specific part of a symbol only. A transparent PET film was attached to the top layer to provide insulation and surface protection. In addition, to cope with the high voltages required, the wiring pattern was created using special printing technology supplied by Kawaguchi Electric Corporation. This allowed us to apply voltages of 1000 V or more to the display.

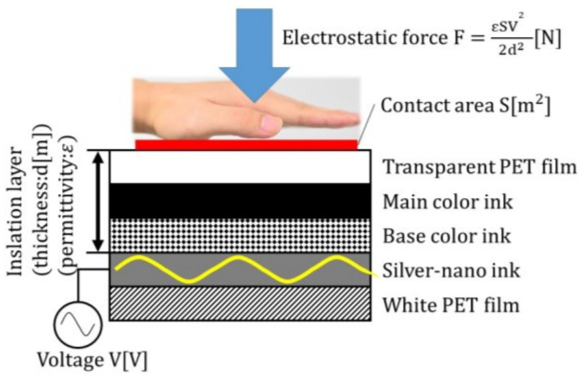

Figure 1. Cross-sectional view of the proposed display and the electrostatic force equation.

The principle of electrostatic tactile displays [8][9][10][11][13] is used in this display. The applied AC voltage changes the electrostatic force periodically. This electrostatic force then changes the frictional force of the contact surface. This periodic change in frictional force presents various textures via electrostatic force between the user's hand and the display surface. An example of the display's use as a poster is shown in Fig. 2. The display has the advantage that it can be rolled up and carried easily (Fig. 3).

Figure 2. Example of display use as a poster.

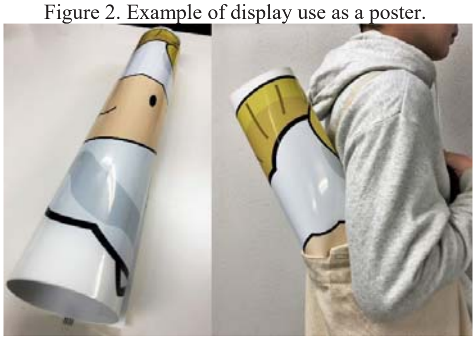

Figure 3. State in which the display can be rolled up and carried.

In this paper, we first verify the effect of the voltage drop on the electrode part that accompanies upsizing of the display (Experiment 1). From the equation shown in Fig. 1, the insulating layer thickness d contributes to the electrostatic attraction force F as a square. This indicates that the insulating layer thickness has a significant influence on the tactile intensity where, as the insulating layer thickness increases, the perceived strength decreases. Therefore, we verify the perceptual strength characteristics of three displays with different insulating layer thicknesses. In Experiment 2, the perceptible lower voltage limit value was investigated using the method of limit for three displays with differing insulation layer thicknesses. In Experiment 3, we used a magnitude estimation method to obtain the transition in the perceived intensity when the applied voltage was increased for the same three displays. In Experiment 4, using a similar magnitude estimation method, we determined the differences in perceived intensity that actually occurred among the three displays when the same voltage was applied to each. These results are then used to examine the influence of the insulation layer thickness on the perceptual strength and its characteristics in this display and the effectiveness of the proposed display is discussed.

III. Experiment 1: Effect of Voltage Drop due to Display Upsizing

A. Purpose

The concern with display upsizing is the inhomogeneity of the electrostatic force distribution due to the voltage drop. Therefore, the voltage drop across the display is measured to verify whether or not a difference that affects the perceptual intensity occurs at each point.

B. Setup and Method

In these experiments, we used a uniformly printed silver nano-ink over the entire A3 (297×420 mm) mount (Card Hi Tester 3244–60, HIOKI). We measured a total of 77 points that moved vertically and horizontally by a distance of 4 cm from the wire connector. A diagram that shows these measurement points is presented in Fig. 4.

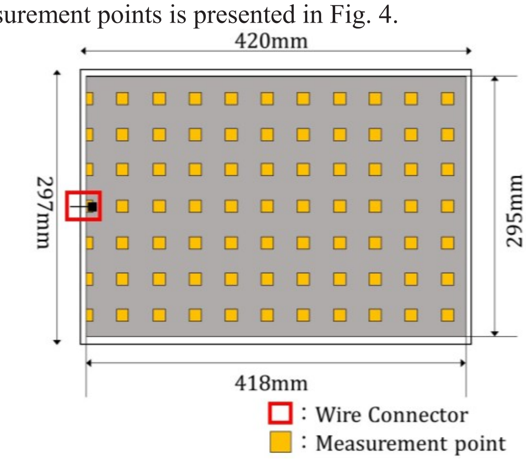

Figure 4. Measurement points of the A3 electrode.

A. Results

In this experiment, the minimum resistance was 0.9 Ω, the maximum value was 1.2 Ω, and the difference was thus 0.3 Ω.

The maximum current under the applied AC voltage was 0.6 mA because of the specification of the high voltage generator used in this device. Therefore, using Ohm's law, it was found that the maximum voltage drop across the electrode layer of the display was 0.18 mV. When electrostatic haptic presentation is actually performed, and because a voltage of several hundred volts is applied to the display, this voltage drop value represents an error of only 0.0001% or less of the input voltage and the users cannot seem to perceive it. Therefore, it can be confirmed that the voltage drop at the electrode layer has no influence on this display.

IV. Experiment 2: Perceptible Lower Limit Voltages of Displays with Different Insulating Layer Thicknesses

A. Purpose

By investigating the lower voltage limit at which the electrostatic force can be perceived in the state in which the symbol is printed on the electrode, the minimum applied voltage required for the proposed display can be verified.

B. Setup

In Experiments 2 to 4, three types of displays, containing silver nano-ink only, silver nano-ink + base color ink, and silver nano-ink + base color ink + main color ink, were prepared to give three displays with different insulating layer thicknesses. The main color ink used in this case was the four-color mixed black ink, which has the largest thickness among all color inks. All inks were applied to the entire surface of each display. Cross-sectional views of the three types of display are shown in Fig. 5. A diagram of the display used in the experiment is shown in Fig. 6. Hereinafter, these three types of displays are referred to as SD (silver nano-ink display), BD (base color ink display), and MD (main color ink display). From previous research, it is known that the thicknesses of the layers of the transparent PET film, the base ink and the printing ink are 12.6 μm, 38.3 μm and 41 μm, respectively. It is thus assumed that the thicknesses of the complete insulating layers in the three displays used in Experiments 2 to 4 are d_{SD}, d_{BD} and d_{MD}, where d_{SD} = 12.6 μm, d_{BD} = 50.9 μm, and d_{MD} = 91.9 μm.

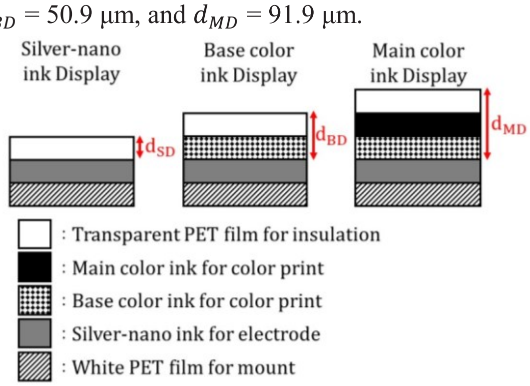

Figure 5. Cross-sectional views of the three types of display.

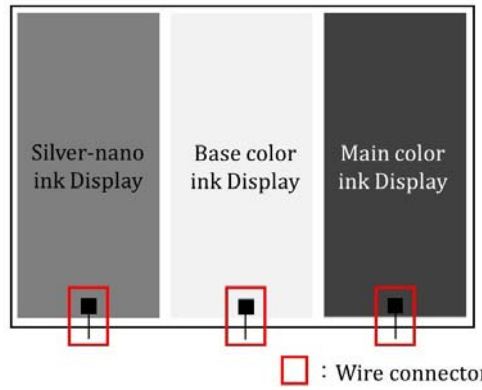

Figure 6. Display used for Experiments 2 to 4.

The equipment configuration used in Experiments 2 to 4 is shown in Fig. 7. By attaching each sample electrostatic tactile display to a Bakelite plate, both vibration and electrostatic force attenuation of the display itself were prevented. The personal computer (PC) and the high-power output device were connected using a Universal Serial Bus (USB) cable via Mbed and were set such that voltage value change commands could be performed via keyboard operations. In addition, the high voltage generator's voltage output terminal was connected to the display and its GND terminal was connected to the GND wrist strap. The high voltage generator was developed at the Kajimoto Laboratory of the University of Electro-Communications [14]. The maximum voltage of this generator is 570 V. The applied AC voltage was set to be a sinusoidal wave of 100 Hz that was confirmed to have high tactile intensity in a previous study [5].

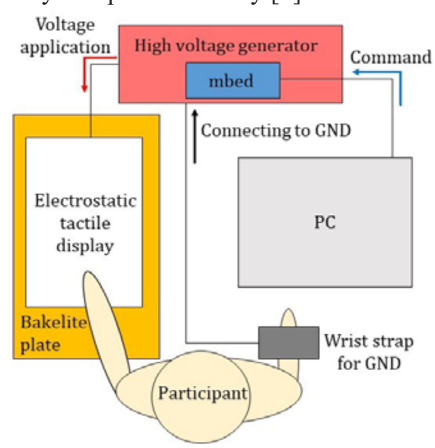

Figure 7. Configuration of the equipment.

C. Method

The experiment was conducted in accordance with the method of limit. In this method, the stimulus strength is typically changed continuously from a sufficiently large/small value. The task of the test participant is to answer whether or not the stimulus could be detected (e.g., visible/invisible). The point at which the participant's response changes (e.g., visible → invisible, invisible → visible) is regarded as the threshold.

For a single voltage value, the subjects alternately traced the surface to which the voltage was applied and the surface to which no voltage was applied from top to bottom for an arbitrary number of times. Subsequently, each subject answered with one of two choices as to whether or not there was a difference in tactile sensation between the two surfaces. In addition, the subjects were instructed to trace for 1 s based on presentation of a metronome signal from their headphones.

First, the voltage value was reduced from 570 V, which is the maximum value that can be output, in 50 V increments, and the reference value was set such that the subjects were able to answer whether or not a difference could be perceived between the two aspects described above. If the voltage value that the subject felt differed finally was *X* V, *X* V was then used as the reference value when the voltage was increased and *X* + 100 V was used as the reference value when the voltage was reduced. This step was performed to shorten the experimental time.

The voltage was subsequently increased or reduced from the reference value in 10 V increments. When the voltage was increasing, the voltage value at which the user first felt the difference was recorded, and when the voltage was descending, the voltage value at which the difference was felt last was recorded.

Recording of the voltage values when the voltage was ascending and descending was performed as one experimental set, and three sets were acquired for each display, as shown in Fig. 5. The experimental order was three times for each display (SD→BD→MD) and data were recorded from a total of 18 trials.

The test subjects were five males, aged 21 to 26 years old. All subjects were able to wipe their hands and the displays using tissue paper at arbitrary times to prevent tactile attenuation due to hand sweat.

D. Results

Experimental results that summarize the ascending and descending data for each face are shown in Fig. 8 in the form of a box plot diagram.

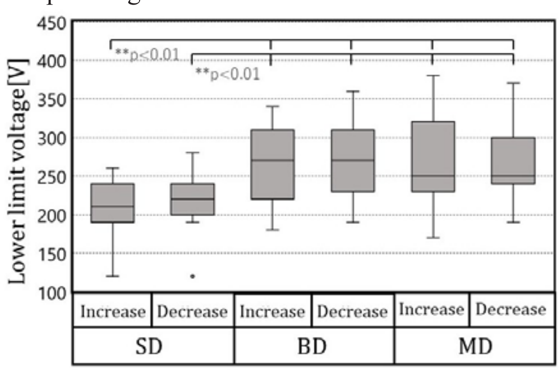

Figure 8. Box plot diagram for Experiment 1.

It was found that tactile sensation can be perceived even when the color ink was applied. Furthermore, the lower limit threshold value for both BD and MD was approximately 250 V, which was 40 to 60 V higher than SD. However, despite the thicknesses of their insulating layers differing by 41 μm, no significant difference was found in the lower limit of the perceived intensity between BD and MD. These results suggest the possibility that the perceptual intensity of the SD is stronger than that of the other displays and there is no significant difference in perceptual intensity between the BD and MD at any voltage.

V. Experiment 3: Measurement of Relationship between Applied Voltage and Perceived Intensity for Each Display with Different Insulating Layer Thicknesses

A. Purpose

There is a possibility that the insulating layer thickness affects the relationship between the applied voltage and the perceptual intensity. Therefore, we investigated the perceptual intensity transition when the applied voltage was increased with respect to the three displays in Fig. 6.

B. Setup

The same experimental equipment and same three displays used in Experiment 2 were also used for this experiment.

C. Method

The experiment was conducted in accordance with the magnitude estimation method. This is a method used to estimate the sensed magnitude directly relative to the physical quantity of the stimulus using numerical values by defining one reference stimulus and comparing it with stimuli of various sizes. From the results of Experiment 1 and several preliminary experiments, 360 V, which each subject could perceive stably, was set as the minimum voltage and thus as the reference stimulus voltage. Stimuli at four voltage values of 360 V, 430 V, 500 V, and 570 V, which varied from the minimum of 360 V to the maximum of 570 V in increments of 70 V, were presented as comparison stimuli in a random order and were compared with the reference stimulus.

Subjects were subjected to auditory blocking using an eye-mask for visual disconnection in combination with white noise presentation from headphones. The subjects first traced the display that presented the reference stimulus (360 V) from the top downward for 2 s. Then, each subject similarly traced a display that presented a comparison stimulus that was randomly selected from 360 V, 430 V, 500 V, and 570 V. The subject regarded the perceived intensity of the reference stimulus as "1" and then estimated the perceived intensity of the comparison stimulus using a free value greater than 0 (the same: 1; half: 0.5; double: 2; feel nothing: 0). Four voltages constituted one set and eight sets of each were performed on the three display types (giving a total of 96 trials). The order in which the displays were presented was varied at random for each subject. To dry the palms of their hands more efficiently than in Experiment 2, the subjects washed their hands with soap before the experiment and always dried their palms using an air blower before performing the tracing motion during the experiment. The test subjects were eight males, aged 21 to 25 years old.

D. Result

Median voltage values for each subject and the estimated values for each display were used as representative values. The representative values for all subjects and the power curve approximated using Excel are shown in Fig. 9. The display type and the voltage values were used as fixed factors, and variance analysis and multiple comparison tests using the Bonferroni method were both performed. As a result, the main effects were observed in both the voltage value (F (3, 84) =

44.408, $p < 0.05$) and the display type (F (2, 84) = 4.619, $p < 0.05$). There was no interaction between these factors (F (6, 84) = 0.386, p = 0.886). From the voltage values, a significant difference was obtained at $p < 0.05$ for all combinations. A significant difference ($p < 0.05$) between the SD and the BD and a significant trend (p = 0.005) shared by the SD and the MD were confirmed by the comparison according to the display type. There were no significant differences between the BD and the MD.

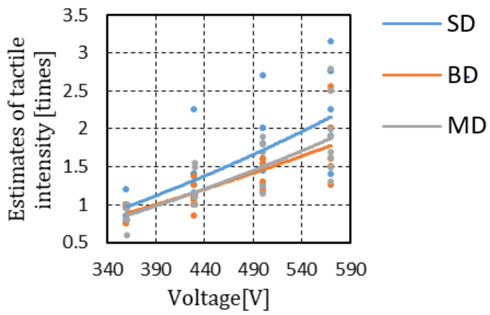

Figure 9. Representative values for all subjects and approximated power curve.

From the results of Experiments 1 and 2, it is possible to obtain a perceived intensity difference that is nearly twice as large as the applied voltage difference in all the displays, but there is no large difference between the BD and the MD in the perceptual intensity change rate.

VI. Experiment 4: Comparison of Perceived Intensity Between Displays Under Constant Voltage Value Condition

A. *Purpose*

In response to the results of Experiment 3, the perceived intensity difference between the three displays generated when 360 V (the reference voltage of Experiment 3) was applied was verified, and the relative difference in perceived intensity based on the applied voltage fluctuation was obtained.

B. *Setup and Method*

The same displays were used in Experiments 2 and 3. A voltage of 360 V was applied to all displays. First, a display for use as a reference stimulus was presented to the subject, and the subject performed the tracing operation twice. Subsequently, another display was presented to provide a comparison stimulus and the subject also traced this display twice. As per Experiment 2, each subject then answered using a free value greater than 0 to express how much stronger the perceived intensity of the comparison stimulus had appeared to be when compared with the perceived reference stimulus intensity. The combination of the three reference stimuli and three comparative stimuli gave a total of nine trials. One set was thus deemed to be nine trials and we performed 6 sets of trials, thus giving 54 trials in total. The ordering of the combinations of the presented reference stimulus and the comparative stimuli were varied at random for each set and for each subject. Conditions including hand drying, blocking of auditory perception and presentation of the metronome were the same as those used in Experiment 2. This experiment was conducted with eight adult male subjects, aged from 21 to 26 years old.

C. *Results*

The median estimates for each combination for each subject were used as the representative values. The averages of the representative values for the eight participants for all combinations of the reference stimulus and the comparison stimuli are shown in Table I. A graph illustrating the transitions in the estimated values of the perceived intensity for each display used to provide the reference stimulus is shown in Fig. 10.

TABLE I. Estimated Values for All Combinations [times]

		Comparison stimulus		
		MD	BD	SD
Reference stimulus	MD	1.0313	1.1375	2.0219
	BD	0.9813	1.125	1.9313
	SD	0.4531	0.5375	1.1469

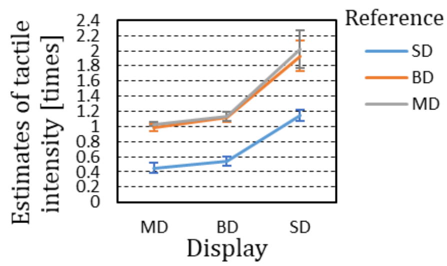

Figure 10. Estimated values of perceived intensity for each display.

Assuming that MD: BD: SD represents the ratio of the estimated values for each reference voltage, MD: BD: SD is 1: 1.10: 1.96 when the reference stimulus is provided by MD, 1: 1.15: 1.97 in the BD case, and 1: 1.19: 2.53 in the SD case (rounded off at the third decimal place). The average of these three ratios is 1: 1.14: 2.15. As these results show, the difference between the perceived intensities of the MD and the BD (1: 1.14) is larger than that between the perceived intensities of the MD and the SD (1: 1.88) and that between the BD and the SD (1.11: 1.75 = 1: 1.58). Therefore, it is believed that there was no significant difference in the rate of change between the MD and the BD when the rate of change in each display was obtained in Experiment 3 because the difference in perceived intensity that actually occurs is small.

VII. Discussion

In Experiment 1, it was clarified that the voltage drop at the electrode layer has no effect on display performance and that uniform tactile presentation over a large area is possible. From the results of Experiment 2, it was found that electrostatic tactile sensation can be generated by applying voltage values of approximately 250 V or more, even in the state where the color ink is printed. This suggests this display would be useful as a poster. From the results of Experiments 3 and 4, we multiplied the ratio of the perceptual strengths of the displays determined in Experiment 4 (1: 1.14: 2.15) by the estimated value for each subject determined in Experiment 3. As a result, we obtained a squared approximation that represented the relationship between applied voltage and perceptual strength that included the perceptual strength ratio that actually occurred among the displays (Fig. 11).

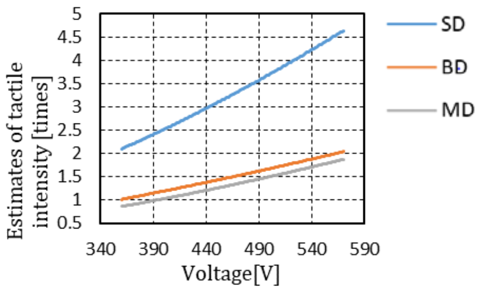

Fig. 11. Relative applied voltage/perceptual intensity curve between the displays.

From the results of Experiments 3 and 4, no significant differences were found between BD and MD in terms of perceived intensity and change rate. Therefore, vivid printing using large amounts of color ink was possible, and the usefulness of this display as a poster became clear. However, a large difference appears between the SD and the other two displays, which suggests that it is possible to increase the perceptual strength partially by eliminating the color inks (base color ink and main color ink) from the design.

In addition, the value of $1/d^2$ for each of the displays is $1/d_{SD}^2 = 62.99 \times 10^8$ for the SD, $1/d_{BD}^2 = 3.86 \times 10^8$ for the BD, and $1/d_{MD}^2 = 1.18 \times 10^8$ for the MD. Therefore, the difference in perceived intensity with respect to the insulating layer thickness is approximately 3.3 times between the MD and the BD, approximately 53 times between the MD and the SD, and approximately 16 times between the BD and the SD. However, when the results of Experiment 4 are considered, the magnification of the result in this case was significantly smaller than the magnification above. In particular, it can be said that there was almost no difference between BD and MD. As the cause of this behavior, it is believed that the permittivity ε of the insulating layer may reduce the perceptual intensity difference. However, the permittivities of the base ink and the printing ink have not been investigated, to date. In further study, by measuring the permittivities of the base color ink layer and the main printing color ink layer, we will realize more accurate design of the texture information.

VIII. Conclusion

We have developed a large printable electrostatic haptic display using electrostatic tactile and paper electronics technology. In this display, it is possible to impart tactile sensation to only a specific part of a symbol by printing a color ink for a symbol on the electrode. Use of the paper medium makes the display easy to enlarge and develop at low cost and it can be rolled up, miniaturized and carried easily. The results of Experiment 1 showed that the voltage drop due to the increase in the size of the proposed display does not affect the perceived intensity. Furthermore, from Experiment 2, it was found that electrostatic tactile sensation can be generated. The possible use of this display as a poster is also shown. From Experiments 3 and 4, it was clarified that the printing of vivid patterns with increased amounts of ink is possible and the usefulness of this display as a poster became clear. However, it may be possible to increase perceptual intensity partially by eliminating the color inks. In future study, we will measure the permittivities of the insulation layers of BD and MD. From the results, we will estimate the electrostatic attraction force and design the texture information for the electrostatic tactile sensation more accurately. In addition, by emphasizing the contours of the touched symbol, we will establish a method to present the shape more clearly to the user and aim for actual use as a poster. If this display is completed, it will be applicable to all existing posters, thus enabling people to convey information more impressively to the experiencer. In addition, while there are currently many electronic advertisements, the utility of posters in paper media can be improved by this display. Furthermore, if applied to a picture book, users can touch objects that cannot usually be touched.

Acknowledgment

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