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A new type of a large-area multi-touch tactile device operated by electrotactile stimulation

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***Abstract*—A new type of a large-area multi-touch tactile device operated by electrotactile stimulation is proposed. Being able to stimulate as many types of mechanoreceptors as possible, the use of electrical stimulation is widespread. However, the area of a device is usually limited because the more electrodes a device is composed of, the more difficult wires are placed if we want to deliver different signals to different regions of one touch panel simultaneously. To get closer to the possibility of integrating multi-touch tactile devices operated by electrotactile stimulation into smartphones or other flat-panel displays, this paper focuses on developing a large-area electrotactile display device driven by electrotactile stimulation that can fully cover smartphones, which has the advantages of larger touched area and better resolution comparing to traditional ones. It is also capable of delivering different stimulation simultaneously on the same surface. The new type of touch panel with cathodes-surrounding anodes taking responsibility for delivering signals and cathodes playing the role of switches to divide signals.**

Keywords—Electrotactile display, large-area tactile device, multi-touch panel.

I. Introduction

Mechanoreceptors are sensory receptors that respond to mechanical pressure or distortion. Among mechanoreceptors, Meissner's Corpuscles, Merkel Cells and Pacinian Corpuscles are mainly responsible for sensation of texture [1] [2] [3]. Therefore, how to stimulate mechanoreceptors is an important key to displaying texture. There are three main methods to generate tactile stimulation: mechanical and vibration stimulation [4] [5] [6], electrovibration [7] [8] and electrotactile stimulation [9] [10]. When it comes to multi-touch haptics, electrovibration is a common method to achieve that goal. For example, Taku Nakamura and his team utilized multiple contact pads to provide haptic feedback to multiple fingers [11]. On the other hand, Hiroshi Haga and his team designed a structure that X electrodes with a waveform crossed Y electrodes with different one [12]. To excite different X or Y electrodes in different regions could bring about different tactile sense. However, electrotactile stimulation, which has the great advantage over others for stimulating more types of skin receptors, is a more attractive method to present tactile sensation [13]. The principle of electrotactile stimulation is using electrical current to pass through the skin and then directly stimulate the sensory nerves. By combining different stimuli, which could generate different tactile sense [14], Michele Germani and his team proved that it had potential for converting real material properties into electrotactile stimulation by scanning real material samples [15]. Here are other multi-touch applications of electrotactile stimulation that have been proposed. K.A. Kaczmarek and his team revealed an electrode fingertip array, which covered a 54 mm by 54 mm touched area [16]. Hiroyuki Kajimoto and his team invented an electrotactile display device for the visually impaired users to detect surrounding view, which covered a 81.28 mm by 40.64 mm touched area and could converted real images into tactile images [17]. They used the smartphone to acquire surrounding view and then converted it into a pixel image on the LCD. After that, they captured the pixel image by the optical sensors and then generated the corresponding electrotactile stimulation. They also came up with a transparent device with ITO-coated glass, which covered a 29 mm by 29 mm touched area [18]. All applications above had the ability to present tactile images of simple geometric shapes but were not good for presenting different textures in different regions of the same surface, except Michele Germani’s device, which covered a 109.5 mm by 25.5 mm touched area and had the better resolution 7 mm [15].

We noticed that the former studies either had the disadvantage to deliver different signals to different electrodes simultaneously, or had a relatively small touched area. It sounds reasonable to deliver different signals to different electrodes by connecting wires that are independent of each other. However, this method will no longer be useful when it comes to a dense electrode array. Because of the limited space between two electrodes, the more electrodes there are in the middle area of an array, the narrower the wires should be. This will cause the problem that the narrow wires are not only harder to be made, but damaged more easily as touched. Hiroyuki Kajimoto and his team applied the design of multiple contact pads to deliver different stimuli to different fingers [19]. In this way, the dense electrode array was not a problem anymore when it came to large-area multi-touch tactile devices. However, this method accompanied the disadvantage that users had to drag pads with cables and that might cause inconvenience. In order to fabricate a large-area multi-touch tactile device without annoying cables, we came up with a brand new design to solve the problem. This improvement made the application of electrotactile stimulation more flexible and possible. Compared to former studies, we had the advantages of the larger touched area 100 mm by 60 mm, the better resolution 2 mm and the ability to deliver different stimulation simultaneously. Combined with through glass via laser drilling technology [20], what can make the 0.1 mm diameter of plated through holes in glass, it will be possible to transfer the bakelite sheet used in this paper into ITO-coated glass and then integrate the device into smartphones or other flat-panel displays.

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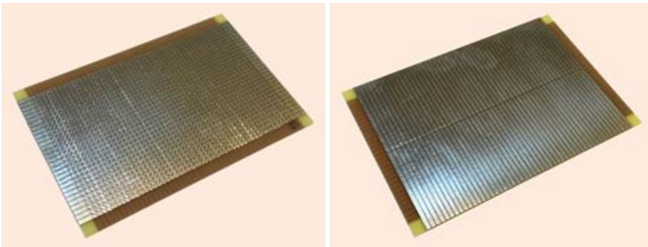

Figure 1. Top side (left) and bottom side (right) of the double-sided electrotactile touch panel with cathodes-surrounding anodes.

II. SYSTEM

A. Hardware System

The system is composed of a DC power supply, a power amplifier, a micro controller, a control circuit and a touch panel. The micro controller, Arduino Mega 2560, and the control circuit convert direct current amplified by the power amplifier into different voltage pulses and then deliver the signals to assigned anodes on the touch panel along with switching on or off assigned cathodes.

B. Design of Electrotactile Touch Panel with Cathodes-Surrounding Anodes

To deal with the issue that the touched area of multi-touch tactile device operated by electrotactile stimulation is limited in past studies, we designed a brand-new type of the touch panel with cathodes-surrounding anodes. There are 60 strip-shaped cathodes (2 by 30) surrounding 1,500 round anodes (50 by 30) on the top side of the panel, and 100 wires (50 by 2) on the bottom side. The anodes in each row connect to each wire, which is parallel to the rows of anodes and perpendicular to cathodes, and pass through the bakelite sheet (Fig. 2).

The two-point discrimination threshold, one definition of tactile resolution, is around 2 mm at fingertips [21]. Therefore, we set the density of anodes to 2 mm. The distance between an anode and a cathode is 0.2 mm, and the distance between two wires is 0.2 mm too. The anodes and cathodes cover a 100 mm by 60 mm area, which is close to the size of 4.7-inch smartphones. That means the touch panel has potential for integrating itself to a smartphone. The diameter of anodes is 1 mm and the size of cathodes is 50 mm by 1.2 mm. The diameter of plated through holes, which are located in the middle of anodes, is 0.1 mm. Besides, the design of anodes surrounded by cathodes can provide better resolution from 4 mm to 2 mm comparing to traditional device (Fig. 3). More importantly, it is the key to delivering multiple electrotactile stimulation simultaneously as cooperating with our operation system.

C. Operation System

The touch panel consists of four large regions. Each large region is controlled by one micro controller with a control circuit. The large region are divided into four small regions driven by the operation system mentioned below (Fig. 2).

Every anode in a same row receives the same signal simultaneously, and different cathodes are controlled to be conductive or not with different time intervals and repetition frequencies. When participants touch the panel, only the regions, where the anodes receive voltage pulses and the cathodes surrounding the former anodes are conductive, can stimulate participants. As controlling the cathodes in different regions to be conductive or not with short time interval, we can deliver different stimulation in different regions.

D. Design of Signals

The principle of electrotactile stimulation is using electrical current to pass through the skin and then directly stimulate the sensory nerves [22]. Different waveforms can generate different tactile sense [14] [23]. In this paper, we applied different pulse widths, pulse repetition frequencies or pulse voltages to generate different stimuli. The pulse widths varied from 250 μs, 500 μs, 750 μs to 1000 μs. The pulse repetition frequencies varied from 25 Hz, 50 Hz, 75 Hz to 100 Hz. The pulse voltages varied from 160V, 240 V, 320 V to 400 V. It is necessary that the peak current cannot exceed 5 mA, which may cause stinging in fingers under certain conditions [24] [25].

III. EXPERIMENTS AND RESULTS

A. Participants

Ten participants, nine males and one female aged from 19 to 24, volunteered to take part in the following experiment. All members were asked to swipe the touch panel as swiping smartphones as usual because we wanted to simulate the actual usage condition. None of them had tactile impairment. The whole experiment was approved and supervised by Research Ethics Committee for Human Subject Protection, National Chiao Tung University, and standard ethical practices were strictly followed.

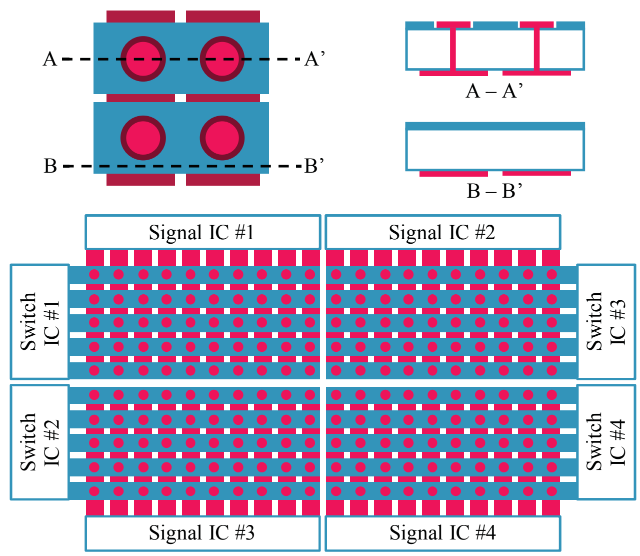

Figure 2. Simplified diagram and drawing of partial enlargement of the electrotactile touch panel with cathodes-surrounding anodes. Red parts are anodes and blue parts are cathodes.

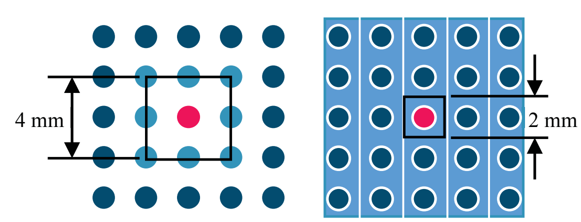

Figure 3. Comparison between structures of traditional touch panels (left) and touch panels with cathodes-surrounding anodes (right). Red parts are anodes with signals, bright blue parts are anodes without signals and deep blue parts are cathodes.

TABLE I. RESULT OF THE STIMULATION TEST AND THE MEAN CURRENT WHEN THE PULSE VOLTAGE VARIED.

	250 μs		1000 μs	
	25 Hz	100 Hz	25 Hz	100 Hz
160 V	20 %	80 %	20 %	90 %
	0.017 mA	0.061 mA	0.060 mA	0.234 mA
240 V	70 %	90 %	90 %	100 %
	0.023 mA	0.094 mA	0.093 mA	0.353 mA
320 V	80 %	100 %	100 %	100 %
	0.037 mA	0.23 mA	0.124 mA	0.471 mA
400 V	90 %	100 %	100 %	100 %
	0.045 mA	0.152 mA	0.154 mA	0.586 mA

TABLE II. RESULT OF THE PEAK CURRENT WHEN THE PULSE VOLTAGE VARIED.

	250 μs		1000 μs	
	25 Hz	100 Hz	25 Hz	100 Hz
160 V	2.72 mA	2.44 mA	2.40 mA	2.34 mA
240 V	3.68 mA	3.76 mA	3.72 mA	3.53 mA
320 V	5.92 mA	4.92 mA	4.96 mA	4.71 mA
400 V	7.20 mA	6.08 mA	6.16 mA	5.86 mA

TABLE III. RESULT OF THE STIMULATION TEST AND THE MEAN CURRENT WHEN THE PULSE VOLTAGE WAS 240 V.

	250 μs	500 μs	750 μs	1000 μs
25 Hz	70 %	80 %	90 %	90 %
	0.023 mA	0.047 mA	0.073 mA	0.099 mA
50 Hz	90 %	90 %	90 %	90 %
	0.046 mA	0.092 mA	0.139 mA	0.169 mA
75 Hz	80 %	80 %	90 %	90 %
	0.070 mA	0.145 mA	0.205 mA	0.263 mA
100 Hz	90 %	80 %	90 %	90 %
	0.096 mA	0.183 mA	0.271 mA	0.367 mA

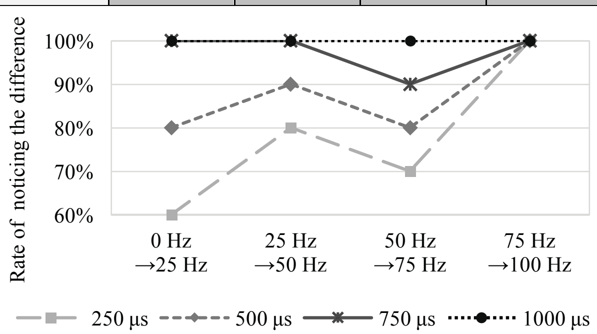

Figure 4. Influence of adjusting the pulse repetition frequency.

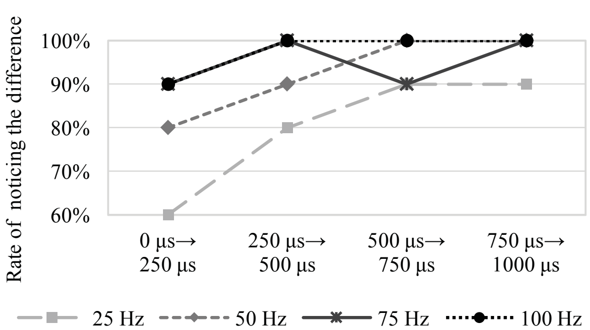

Figure 5. Influence of adjusting the pulse width.

B. Stimulation Test

To verify that the electrotactile touch panel with cathodes-surrounding anodes could deliver stimulation, we conducted the first test. First, the participants were asked to swipe the touch panel without any voltage pulse. Second, we applied a certain voltage pulse and then asked the participants whether they could feel the stimulation along with recording the mean current. Third, we adjusted the pulse voltage to verify which pulse voltage was proper, and then repeated step 2 as changing the pulse width or the pulse repetition frequency.

Table I shows the percentage of participants who could feel the stimulation when the pulse voltage varied. It also shows the relationship between the mean current and the different voltage pulses. Table II shows the relationship between the peak current and the different voltage pulses. We discovered that not only the mean current but also the peak current could affect the number of participants who could feel the stimulation. All participants indicated that the stimulation got greater and greater as we increase the pulse voltage. However, the peak current over 5 mA might cause stinging in fingers. We noticed that 40% participants could feel stinging when the pulse voltage was over 320 V. Therefore, we concluded that the voltage pulses within 240 V and 320 V, which could make at least 70% participants feel the stimulation, was ideal for the following tests.

Table III shows the percentage of participants who could feel the stimulation when the pulse width or the pulse repetition frequency varied. At least 70% participants could feel the stimulation. In addition, the higher the pulse repetition frequency was, the more participants could feel the stimulation. The wider the pulse width was, the more participants could do so too. This table also shows the mean current as applying different voltage pulse. We discovered that the percentage of participants who could feel the stimulation raised as the mean current raised. More than 80% participants could feel the stimulation as the mean current exceeded 0.046 mA. This test proved that the electrotactile touch panel with cathodes-surrounding anodes could deliver stimulation successfully with different voltage pulses, and the mean current as well as the peak current played important role in causing effective stimulation.

C. Influence of Adjusting Voltage pulses

To verify that the users could feel different stimulation, we conducted the second test. First, the participants were asked to swipe the touch panel applied a certain voltage pulse. Second, we adjusted the properties of the voltage pulse, the pulse width or the pulse repetition frequency, and then asked the participants whether they could notice the difference of tactile sensation along with recording what kind of variation they felt. The pulse voltage was kept at 240 V.

Figure 4 and figure 5 show the percentage of participants who could notice the difference of tactile sensation as we adjusted the pulse width or the pulse repetition frequency respectively. At least 60% participants could notice the difference no matter which property we adjusted. We discovered that the higher the pulse repetition frequency was, the more participants could notice the difference as the pulse width varied. The wider the pulse width was, the more participants could do so as the pulse repetition frequency varied. Besides, 50% of participants indicated that roughness changed as we adjusted the pulse repetition frequency, and another 50% indicated the sense that changed was the vibratory sensation. Moreover, 90% of participants described what difference they noticed was the granular sensation as we adjusted the pulse width, and another 10% said that they felt the intensity of entire stimulation vary. This test proved that the electrotactile touch panel with cathodes-surrounding anodes could deliver 16 kinds of stimulation by composing different pulse repetition frequencies and different pulse widths. We could foresee that the difference of stimulation would increase if mixing different waveforms like sine wave, triangle wave, noise, and so on.

D. Comparison between Traditional Device and Touch Panel with Cathodes-surrounding anodes

To compare the performance of traditional electrotactile display devices and the electrotactile touch panel with cathodes-surrounding anodes, we conducted the third test. First, the participants were asked to swipe the traditional electrotactile display device and the electrotactile touch panel with cathodes-surrounding anodes without any voltage pulse. Second, we applied same voltage pulses to both devices and then asked the participants whether they could feel the stimulation and which device could deliver the stronger stimulation along with recording the mean current. Third, we adjusted the properties of the voltage pulse, the pulse width or the pulse repetition frequency, and then repeated step 2.

Figure 2 shows the difference of structures on two devices. It is notable that the interval of two signal sources was 4 mm but not 2 mm on the surface of the touch panel with cathodes-surrounding anodes. The reason was that eight cathodes should surround one anode to deliver effective stimulation as it came to traditional devices, and that caused the interval of two signal sources 4 mm. Table IV shows the percentage of participants who could feel the stimulation and the mean current as we applied different voltage pulses. We noticed that both devices could make all participants feel the stimulation, and the stimulation were almost alike except the intensity. Figure 6 shows the percentage of participants choosing which device could deliver stronger stimulation. The intensity of stimulation that the traditional electrotactile display device delivered was stronger than that delivered by the electrotactile touch panel with cathodes-surrounding anodes. As comparing the mean current of two devices, we were stunned that the mean current of the electrotactile touch panel with cathodes-surrounding anodes was five times greater than another one.

With this result came two questions. The first one was why all participants could feel the stimulation as swiping the electrotactile touch panel with cathodes-surrounding anodes in all conditions in this test, but only 70% participants could do so in the worst condition when we conducted the first test. There was a possibility that the two-point discrimination threshold of some participants might exceed 2 mm, so they could not feel any difference as all anodes were applied the same voltage pulse with the narrow pulse width and the low pulse repetition frequency. Even though further research is needed to confirm our assumption, this problem did not prevent us from reaching our goal. The second one was why the intensity of stimulation that the traditional electrotactile display device delivered was stronger than that delivered by the electrotactile touch panel with cathodes-surrounding anodes, even if the mean current of the eletrotactile touch panel with cathodes-surrounding anodes was greater. We made the assumption through the simulation of the current-density distribution on fingers touching two devices by ANSYS. Figure 7 shows the current-density distribution of a fingertip as touching the traditional electrotactile display device and the electrotactile touch panel with cathodes-surrounding anodes respectively. The result showed that the current-density distribution was wider in the former condition. It was possible that the traditional device could stimulate more receptors or could pass through the deeper receptors. Still, further research is needed to figure out this question, but the intensity of the electrotactile touch panel with cathodes-surrounding anodes could be enhanced by adjusting pulse voltage. Therefore, it did not prevent us from reaching our goal either.

TABLE IV. RESULT OF STIMULATION TESTS OF THE TRADITIONAL DEVICE (WHITE) AND THE TOUCH PANEL WITH CATHODES-SURROUNDING ANODES (GRAY).

	250 μs		1000 μs	
25 Hz	100 %	100 %	100 %	100 %
	0.003 mA	0.017 mA	0.011 mA	0.071 mA
100 Hz	100 %	100 %	100 %	100 %
	0.012 mA	0.062 mA	0.048 mA	0.223 mA

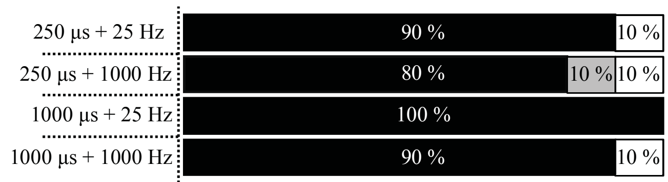

Figure 6. Comparison between the intensity of stimulation of traditional device and the touch panel with cathodes-surrounding anodes. Black means the traditional device is intenser, white means the touch panel with cathodes-surrounding anodes is intenser, and gray means they are equal.

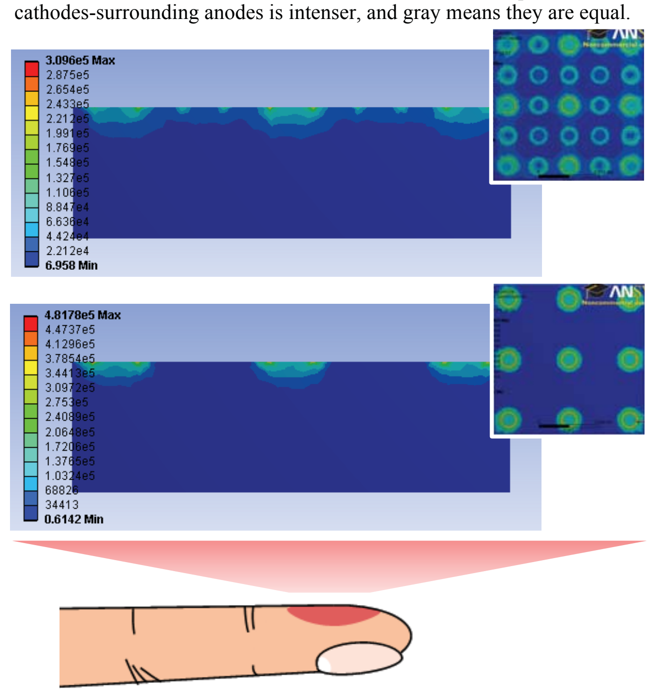

Figure 7. Simulations on the current-density distribution of a fingertip touching the traditional device (top) or touching the touch panel with cathodes-surrounding anodes (bottom).

E. Multiple Electrotactile Stimulation Test

To verify that the double-sided electrotactile touch panel could deliver multiple electrotactile stimulation simultaneously, we conducted the last test. First, we used LED bulbs to touch electrodes in different regions. Second, the participants were asked to swipe every two large regions applied different voltage pulses with left and right index fingers respectively at the same time (Fig. 8). Second, we asked them whether they could notice the difference between two regions. All steps were same when we tested small regions. The pulse voltage was kept at 240 V.

As we used LED bulbs to touch different regions at the same time, we could see they were blinking with different time intervals no matter we tested large regions or small regions. In addition, figure 9 shows the percentage of participants who could notice the difference between two regions. At least 80% participants could do so as we tested large regions and 70% as we tested small regions. This result indicated that our design could achieve the goal that was to develop a large-area multi-touch display device by electrotactile stimulation.

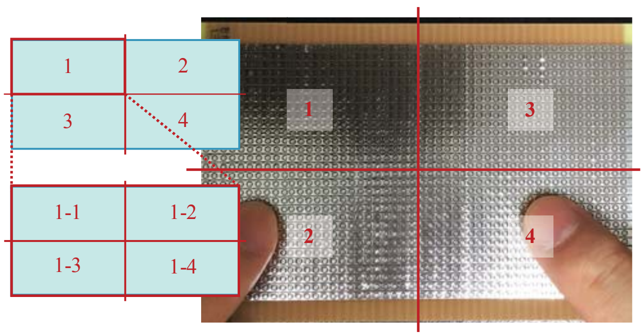

Figure 8. Overview of the touch panel with cathodes-surrounding anodes. Every large region is divided into four small regions.

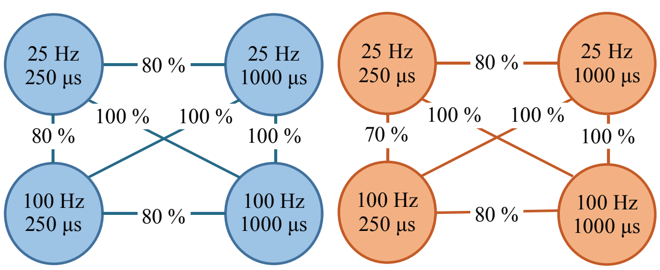

Figure 9. Result of multiple electrotactile stimulation test when participants compared large regions (left) and small regions (right).

IV. Conclusion

In this paper, we succeed in developing a large-area multi-touch tactile device by electrotactile stimulation, which has four main advantages: First, the resolution has been improved from 4 mm to 2 mm. Second, the touched area of the device has been enlarged to 100 mm by 60 mm. Third, it can deliver 16 kinds of different stimulation. Last, the device can deliver different stimulation to different regions simultaneously.

This result shows the further possibility of combining multi-touch tactile devices operated by electrotactile stimulation with smartphones or other flat-panel displays. Thanks to Hiroyuki Kajimoto and his team's successful transparent device with ITO-coated glass [18] and mature through glass via laser drilling technology [20], it is convinced that the same material could substitute the bakelite sheet at the next step. Our ultimate goal is to make the touch panel into a screen protector and to integrate other hardware system into a smartphone case or to transfer the control system from micro controller to flat-panel displays in order to lighten the device. In addition, we will conduct the threshold experiment, regulate the electric current and evaluate the effect of electrode spacing of the structure we designed. As more and more researchers are devoted themselves to creating database of the relationship between tactile sensation and electrotactile stimulation, we can look forward to combining the database and our new design together into an advanced multi-touch tactile device that will provide more realistic tactile sensation.

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