MonoTouch: Single Capacitive Touch Sensor that Differentiates Touch Gestures

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Abstract
We show a capacitive touch sensor called MonoTouch, which differentiates taps, swipe gestures, and swipe directions. MonoTouch consists of only an electrode and a circuit. To differentiate touch gestures with a single electrode, we designed the electrode's layout to satisfy the following two requirements: (1) The number of responses is different between the gestures; (2) The response time is different between swipe directions. We then developed an electrode that differentiates taps and four directional swipe gestures. When our MonoTouch electrode is downsized, gesture differentiation accuracy decreases because a finger might cross two or more conductive parts. To solve this “Multiple Crossing Problem”, we added embossments on the electrode surface. Our evaluation of the MonoTouch sensor indicates that using the embossments solved the “Multiple Crossing Problem”.

Author Keywords
Touch gesture differentiation; single electrode; 3D print; rapid prototyping.

ACM Classification Keywords
H.5.2 [Information interfaces and presentation (e.g., HCI)]: User Interfaces - Input devices and strategies (e.g., mouse, touchscreen); Prototyping

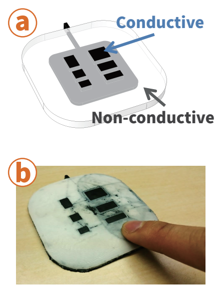


Figure 1: MonoTouch.

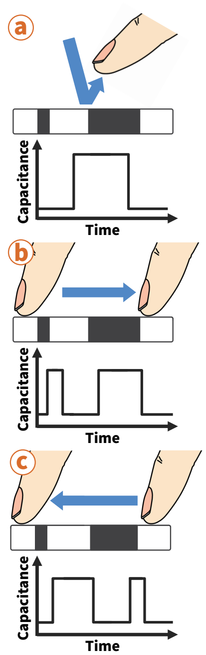


Figure 2: Responses for each gesture: a) tap, b) forward swipe, c) backward swipe.

Introduction

A capacitive touch sensor detects a finger touch by measuring the variation of capacitance of the sensor's electrode. A popular technique to measure the variation is based on the resistance-capacitance (RC) time constant of an electrode, which can be observed through a single connection to the electrode; this result in an interface structure that is simple. However, capacitive touchscreens and touchpads, which are used as input devices for computers, consist of multiple electrodes. To measure the capacitance of each electrode, these devices require many connections. By contrast, if gesture differentiation is available using only a single electrode, designing the interface becomes simpler because it requires only a single connection. For example, this is useful in producing 3D printed interactive figures. Manabe et al. proposed a technique that allows a single capacitive touch sensor to recognize touch, multifinger swipes, and swipe directions [11]. They used a printed circuit board (PCB) on which they printed two electrodes of different area sizes.

In our system, we designed an electrode layout that can differentiate taps, swipe gestures, and swipe directions using only a single electrode, which we call MonoTouch. To differentiate the five gestures using a single electrode, we designed the layout of the electrode to satisfy the following two requirements: (1) The number of responses is different between gestures; (2) The response time is different between swipe directions. We,next designed and developed an electrode layout that can differentiate taps and four directional swipe gestures based on the aforementioned two requirements as shown in Figure 1. Because of its simplicity, a 3D printer can be used with conductive and non-conductive filaments to print the electrode of MonoTouch. Moreover, we observed that gesture differentiation accuracy decreases when the electrode is downsized. This is because a finger might cross two or more conductive parts. To solve this "Multiple Crossing Problem", we added embossments on the electrode surface.

Related Work

Many types of touch sensors have been proposed: These types include pressure [16, 15], optical [6, 7], capacitive [14, 17], acoustic [8, 13], and time domain reflectometry [21]. Among them, optical and capacitive types can be arranged in an array to form a panel that can differentiate touch gestures [10, 5, 14, 4]. However, several connections are required to construct the array of sensors. Reducing the number of connections ultimately to just one makes designing a touch sensitive object simple.

Several studies have proposed methods to differentiate touch gestures by means of a single electrode. Touché [17] recognizes complex configurations of the hand by means of a single capacitive electrode , which analyzes the signal in the frequency domain. Similar recognition is available through vibration [13]. These techniques are more suitable for recognizing static rather than dynamic touch gestures. Our technique differs from these techniques in that it differentiates dynamic touch gestures.

In addition, a technique that analyzes signals in the time domain has been proposed [20]; This technique differentiates four dynamic touch gestures using two photoreceptors. Furthermore, a method exists that analyzes the vibration in the time domain [9]. Although our technique is similar to these techniques with respect to analyzing the signal in the time domain, we use a single electrode to differentiate touch gestures.

Finally, many types of sensors that are 3D printed using conductive and non-conductive filaments have been proposed [3, 19, 12]. We use this technique to develop the electrode of MonoTouch.

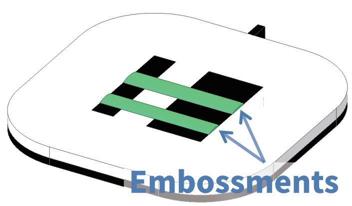


Figure 3: Position of embossments.

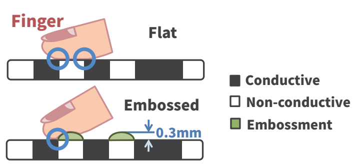


Figure 4: Effect of embossments.

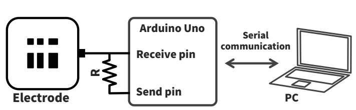


Figure 5: Structure of MonoTouch.

MonoTouch Design

We show the pattern of a single electrode, which consists of multiple conductive parts, that can differentiate taps and swipes (including swipe directions) based on the response, as shown in Figure 2. We also show embossments to be added to the electrode's surface, which makes the electrode small while maintaining gesture differentiation accuracy.

Layout Requirements

To differentiate taps and swipes, we designed the layout to meet the following design requirements:

[Requirement 1] To differentiate tap from other touch gestures, we designed the layout with multiple conductive parts that are each separated by a non-conductive part. With this design, when a user taps the electrode, his or her finger comes into contact with one or several conductive parts simultaneously. Thus, the sensor identifies a single response, as shown in Figure 2a. By contrast, when the user swipes his or her finger on the electrode, the finger comes into contact with multiple conductive parts successively. Thus, the sensor identifies multiple responses as shown in Figure 2b and c. Therefore, counting the number of responses can differentiate taps from other touch gestures.

[Requirement 2] We designed each conductive part with a unique size so that the electrode has an asymmetric sensor response depending on the swipe direction. For example, when a user swipes right to left, the user first touches a large part, then a small part, as shown in Figure 2c.

Addition of Embossments

When the electrode is downsized, the accuracy of gesture differentiation decreases because a finger might cross two or more conductive parts. To solve this "Multiple Crossing Problem", which is similar to the Fat Finger Problem [18], we added embossments on the surface of the electrode as shown in Figure 3. These embossments may solve the "Multiple Crossing Problem" as shown in Figure 4.

Implementation

As one implementation for the electrode's many possible layouts, we designed a layout that can differentiate taps and four directional swipes based on the aforementioned two requirements. We used a 3D printer (FLASHFORGE, Dreamer, 0.4mm nozzle) to generate the electrode with both conductive (Proto-pasta, Conductive PLA) and non-conductive filaments (FLASHFORGE, PLA). Because the 3D printer has dual printer heads, we were able to 3D print both the conductive and non-conductive filaments in a single attempt. In this manner, the conductive filament is directly built into the non-conductive part without additional assembly. This design is not affected by the size, and thus is scalable, and limited by the printer's size itself. We then developed a touch sensor that can detect taps and swipes based on the variation of capacitance. This sensor is called MonoTouch, the structure of which is presented in Figure 5.

Measuring the Variation of Capacitance

To measure the variation of capacitance, we use CapSense [1] which is a library for Arduino. This library uses an RC time constant, defined by $R \times C$ to measure the variation of capacitance. In this equation, R is the resistance value of the resistor that is attached between the send and receive pins, and C is the capacitance at the receive pin plus any other capacitance (e.g., human body) present.

Gesture Differentiation

Figure 6 shows the detected response wave form with a low pass filter applied. In the middle part of each image in Figure 6, the vertical axis refers to capacitance. The horizontal axis refers to a frame that is updated at every measurement. The lower part of each image shows the difference

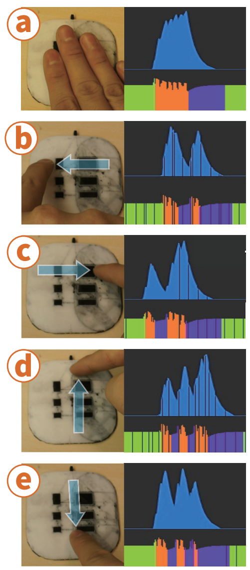


Figure 6: Response wave forms (a: tap, b: left swipe, c: right swipe, d: up swipe, e: down swipe). For the purpose of illustration, we only show interactions with the upper row and right column. In fact, all the conductive parts can be used to differentiate gestures.

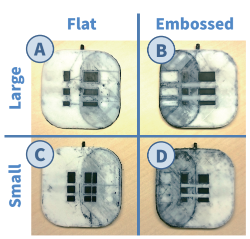


Figure 7: The electrodes that were used in the evaluation.

between the previous two frames. If the difference is positive, the wave is colored in orange. If the difference is negative, the wave is colored in purple. Otherwise, the wave is colored in green.

To differentiate gestures, the system first considers that a gesture starts when the response begins to rise and ends when the response drops to zero. The system then reviews the number of positive sections, and determines whether the first section is longer than the last. The main difference between the system of Manabe [11] and our own is that Manabe's can detect two directional swipes, whereas ours can detect four or more. Moreover, Manabe's system observes the shape of the response wave in order to detect touch gestures, whereas ours uses the number and widths of responses.

Evaluation

We conducted a user study to examine the effect of the size and embossment of electrodes on accuracy.

Design

Factors

This user study considered two factors for the electrode: size (Small: square with a side of 25 mm, Large: square with a side of 30 mm) and shape (Flat or Embossed). Therefore, we developed four electrodes (A–D) as shown in Figure 7, having sizes given in Figure 9, where "nc" represents the size of the non-conductive part. The electrode layout was embedded in the center of a square of non-conductive filament with a side of 70 mm. In the Embossed condition, we produced embossments with a height of 0.3 mm.

Participants

The participants were eight volunteer university undergraduates and graduate students (P1–P8), all right-handed males between 22 and 24 years old. All participants were familiar with taps and swipe gestures in using a smartphone. We measured the size of their right index finger (i.e., width, thickness, and areasize = width $\times$ thickness) at the location shown in Figure 8 using a digital caliper. Table 1 lists those sizes.

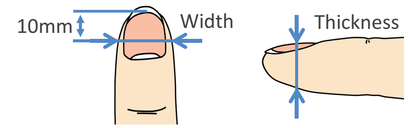
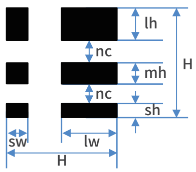


Figure 8: The location of measurement of index finger size.

Task

The participants conducted the task while sitting. They were instructed to use only the tip of their right index finger for swiping, and that the finger must vertically point downwards when they swiped. However, they were not instructed to use a particular rate of speed while swiping. they were also asked to use four fingers with the palm faced down when they tapped. They were told to familiarize themselves with the five touch gestures (i.e., tap, up swipe, down swipe, right swipe, and left swipe) using the practice program, which displays the response of the sensors and the differentiated gestures. The participants trained until they were familiar with the gestures.

Following a practie session, each participant was asked to complete the evaluation task. He conducted one session with each of four electrodes. In a session, he performed ten trials using each of the five gestures. In summary, the experiment design involving $8\,participants \times 4\,sessions \times 50\,trials = 1,600\,trials$. The participants received breaks of at least three minutes each between two sessions. The participants were assigned randomly to one of two groups to counterbalance the order effect: one group performed these gestures in the order of electrode A$\rightarrow$B$\rightarrow$C$\rightarrow$D;



	Small	Large
H	25.00	30.00
lh	9.00	9.00
mh	5.64	6.00
sh	4.36	4.00
sw	6.00	6.00
lw	10.00	15.00
nc	3.00	5.50

Figure 9: Sizes in mm of the electrodes shown in Figure 7.

Participant	Width $[mm]$	Thickness $[mm]$	Area size $[mm^2]$
P1	13.87	8.20	113.73
P2	13.36	7.26	96.99
P3	12.84	8.72	111.96
P4	10.98	7.19	78.95
P5	13.39	7.38	98.82
P6	12.40	8.17	101.31
P7	12.59	8.36	105.25
P8	12.40	8.28	102.67

Table 1: The size of the right index finger of the participants, in mm.

Participant	Electrode A	Electrode B	Electrode C	Electrode D
P1	2.509	2.268	1.941	2.125
P2	1.957	2.260	2.390	2.301
P3	1.226	0.989	1.675	1.471
P4	1.839	2.084	2.166	2.043
P5	2.227	2.051	2.247	1.982
P6	1.882	1.736	1.620	1.836
P7	1.880	1.594	1.410	1.721
P8	1.614	1.757	1.716	1.696

Table 2: Input time of each participant, in seconds.

Participant	Electrode A	Electrode B	Electrode C	Electrode D
P1	0.98	0.98	0.50	0.80
P2	0.90	0.92	0.80	0.56
P3	0.96	0.72	0.84	0.80
P4	1.00	0.98	0.82	0.68
P5	0.70	1.00	0.68	0.68
P6	0.96	0.98	0.48	0.74
P7	0.84	0.82	0.52	0.46
P8	0.98	0.98	0.72	0.66

Table 3: Accuracy of each participant.

the other group performed these gestures in the order of electrode B→A→D→C. When the participants finished the tasks, they were asked to complete a questionnaire containing three questions. Each participant completed all tasks in approximately 50 minutes.

Results

Tables 2 and 3 show the input time and accuracy of each participant, respectively. Table 4 shows the accuracy of each electrode. The results reveal that the accuracy of electrode B is greater than that of all other electrodes.

Discussion

These results suggest that adding embossments on the electrode surface improves accuracy. They also suggest that the electrode size is the most important factor in gesture differentiation, possibly because of the "Multiple Crossing Problem". By contrast, as Tables 4C and 4D show, up and down swipe accuracy improves when adding embossments on the electrode surface. Therefore, the embossments solved the "Multiple Crossing Problem". [1]

However, the results also reveal that the embossments must be carefully manufactured. According to Table 4B, a down swipe tends to be erroneously detected as a left swipe on electrode B. Note that in both gestures, the first positive section of the response is longer than that of the final one, as shown in Figures 6c and 6e. Regarding this result, when the user's finger was obstructed by the embossments, the sensor determined erroneously that at the halfway point, the gesture was completed. This problem happened especially with Participants P3 and P7. Table 2 shows that the input times of P3 and P7 were shorter than those of the other participants. In addition, in the questionnaire, P3 and P7 each commented that the embossments obstructed the finger. Therefore, producing smoother embossments is necessary in a future study.

To examine the relationship between the accuracy and area size of the finger, we calculated the correlation coefficient between them. (A positive result indicates that the accuracy increases when the finger area size is large).

The results are: electrode A: -0.029; electrode B: -0.428; electrode C: -0.421; and electrode D: 0.272. The correlation coefficients of the smaller electrodes C and D also support the claim that adding embossments solves the "Multiple Crossing Problem" which mainly occurs when the electrode is downsized. Moreover, one participant stated in a response on the questionnaire that eyes-free input could be performed because of the haptic feedback generated by the embossments.

Applications

In this section, we describe some applications that use an electrode printed with a 3D printer. We also present other electrode layouts.

Cover

Figure 10 shows two MonoTouch applications that we developed. Figure 10a is a headphone cover attached to the side of the headphone; it allows the control of a music player. In this example, the gestures are assigned as: next/previous track (right/left swipe), volume up/down (up/left swipe), and play/stop (tap). Figure 10b shows a smartphone cover that realizes Back-of-Device operation [2]. In this case, the user can control a navigation key on the back of the smartphone for use with a web browser.

[1] We conducted a one-way repeated measures ANOVA to investigate differences between two shape conditions. Table 4D shows that the accuracy of up and down swiping of electrode D was significantly higher than that of electrode C (up: $p = 0.000, down: p = 0.049$). This is caused by the fact that poor printing accuracy generates a worse response from the conductive parts in electrode D.

A

Accuracy(Large, Flat)

Input gesture \ Differentiated gesture	TAP	UP	DOWN	RIGHT	LEFT
TAP	100.00%	-	-	-	-
UP	1.25%	93.75%	3.75%	1.25%	-
DOWN	1.25%	6.25%	86.25%	-	5.00%
RIGHT	6.25%	-	-	92.50%	1.25%
LEFT	3.75%	-	-	11.25%	85.00%
				Total	**91.73%**

B

Accuracy(Large, Embossed)

Input gesture \ Differentiated gesture	TAP	UP	DOWN	RIGHT	LEFT
TAP	98.75%	-	-	-	1.25%
UP	1.25%	92.50%	-	6.25%	-
DOWN	1.25%	-	80.00%	-	18.75%
RIGHT	1.25%	-	-	96.25%	2.50%
LEFT	3.75%	-	1.25%	1.25%	93.75%
				Total	**92.25%**

C

Accuracy(Small, Flat)

Input gesture \ Differentiated gesture	TAP	UP	DOWN	RIGHT	LEFT
TAP	97.50%	-	-	1.25%	1.25%
UP	42.50%	35.00%	6.25%	7.50%	8.75%
DOWN	41.25%	-	45.00%	1.25%	11.25%
RIGHT	2.50%	-	-	68.75%	28.75%
LEFT	6.25%	-	1.25%	2.50%	90.00%
				Total	**67.42%**

D

Accuracy(Small, Embossed)

Input gesture \ Differentiated gesture	TAP	UP	DOWN	RIGHT	LEFT
TAP	98.75%	-	-	-	1.25%
UP	-	76.25%	13.75%	3.75%	1.25%
DOWN	3.75%	5.00%	75.00%	-	16.25%
RIGHT	40.00%	1.25%	1.25%	35.00%	22.50%
LEFT	41.25%	-	1.25%	6.25%	51.25%
				Total	**67.93%**

Table 4: Confusion matrix.

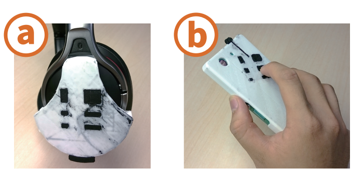


Figure 10: MonoTouch applications (a: headphone cover, b: smartphone case).

Figure

We designed an application that takes advantage of MonoTouch's property that it allows gestures to be differentiated using only a single electrode with a single connection. This application is based on an owl figure we developed, as shown in Figure 11. Printing two or more connections inside a thin portion of the figure (e.g., the bottom part) is difficult. The dual-head 3D printer tends to link the neighboring parts when it uses two filaments simultaneously. This occurs because the filaments are blurred; if we print two connections with a conductive filament, they tend to connect to the blurred filament. By contrast, MonoTouch is designed to be easily embedded, even in an object with a complex shape.

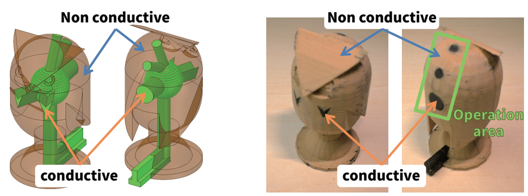


Figure 11: An example of a 3D printed object.

Other Electrode Layouts

In this study, we developed and evaluated an electrode layout that can differentiate taps and four directional swipes. In addition, we developed other electrode layouts as shown in Figure 12. Figure 12a shows an electrode that has debossments and can differentiate eight directional swipes. The right side of Figure 12a shows the wave forms detected when these gestures are performed. Because these wave forms differ from each other, differentiating the eight directional swipe gestures is possible.

Figure 12b shows an electrode that can differentiate rotation gestures. This layout can differentiate the direction of

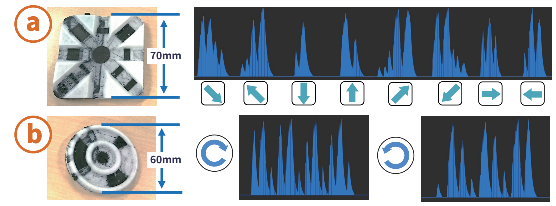


Figure 12: Other examples of electrode layout.

rotation gestures based on the response wave form. If a response wave shifts in the order of Small→Middle→Large, the gesture is a clockwise rotation. If a response wave shifts in the order of Small→Large→Middle, the gesture is a counterclockwise rotation. Moreover, this layout can count the number of rotations based on the number of responses.

Conclusion

In this study, we proposed a technique to differentiate taps and swipes (including swipe directions) using a single electrode. We call this technique MonoTouch. In addition, we developed a system to differentiate five touch gestures by measuring the electrode's capacitance. When the MonoTouch electrode was downsized, gesture differentiation accuracy decreased because a finger might cross two or more conductive parts. To solve this "Multiple Crossing Problem", we added embossments on the electrode surface. The evaluation results indicate that using embossments solved this "Multiple Crossing Problem". In addition, our design is sufficiently simple for the sensor to be 3D printed with both conductive and non-conductive filaments.

In the future, we plan to explore an optimal electrode layout, and will try employ other materials (e.g., PCB, separate cut sheets and conductive parts, and stickers that are printed with conductive ink). We also plan to downsize the electrode.

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