RootCap: Touch Detection on Multi-electrodes using Single-line Connected Capacitive Sensing

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ABSTRACT
In designing interactive products, it is important for designers to test the product's usability by manufacturing its shape and interface iteratively through rapid prototyping. The goal of our research is to provide the designers with an additional touch sensing method for rapid prototyping interactive products with flat, curved, or flexible surface. In this paper, we present RootCap, a capacitive touch sensing method that can detect a touch on a multi-electrode input surface while maintaining the characteristics of a single-line connection. The key concept behind realizing this goal is the imposition of unique capacitance on each electrode (including the capacitor connected to the touch electrode) branching from the single-line connection. Moreover, we developed a technique for creating a capacitor by printing silver nanoparticle ink on both sides of a sheet of paper, supporting designers in the creation of a multi-electrode input surface, on which each electrode has a unique capacitance.

Author Keywords
Touch Surface; Capacitive Sensors; Rapid Prototyping; Paper Prototyping; Digital Fabrication; Conductive Ink; Paper Circuit; Double-Sided Circuit; Flexible Sensor; Gesture Detection.

ACM Classification Keywords
H.5.2. Information interfaces and presentation: User Interfaces - Input Devices and Strategies.

INTRODUCTION
In designing interactive products, it is important for designers to test the product's usability by manufacturing its shape and interface iteratively through rapid prototyping. To this end, manufacturing methods such as stereolithography [10] and fused deposition modeling (FDM) were developed and used, allowing designers to manufacture a small-scale prototypes quickly without using a mold or lathe. In interface manufacturing, many devices—including traditional mechanical devices (e.g., buttons, switches, and sliders) as well as recent touch sensing tools, such as integrated circuits (ICs)—are available. Ready-made multi-electrode touch sensor ICs suite rapid prototyping; they allow designers to place many touchable "buttons" on the surface of their prototypes (even on curved or flexible one), while facilitating the mounting process compared to solder-connected mechanical buttons. Moreover, it also allows the designers to design such buttons in free-form (e.g., circular, star-shaped, and heart-shaped ones).

The goal of our research is to provide the designers with an additional touch sensing method for rapid prototyping interactive products with flat, curved, or flexible surface. Generally, a capacitive touch sensor consists of a touch electrode, a sensing circuit, and a wire that connects the touch electrode and the sensing circuit. As a result, if the designers wish to use N touch electrodes, N sensing circuits and N wires are also necessary. While reducing the number of sensing circuit is made possible by using a multiplexer, this implementation still involves significant complicated wiring and its structures and logic are difficult to implement.

Thus far, myriad touch sensing methods have been developed that may be applied to prototypes with flexible shapes, such as in [9, 14, 4, 15, 16, 8, 7]. Based on this previous work, our focus herein is on:

- Decreasing the number of connections between the sensing circuit and touch sensing electrodes while increasing the number of available touch sensing electrode, and
- Expanding the degree of freedom for the shape and layout of touch sensing electrodes.

In this paper, we present RootCap, a capacitive touch sensing method that can detect a touch on a multi-electrode input surface while maintaining the characteristics of a single-line connection, as illustrated in Figure 1. The key concept behind realizing this goal is the imposition of unique capacitance on each electrode (including the capacitor connected to the touch electrode) branching from the single-line connection. As the result, when the user touches a touch electrode, a different capacitance is observed via the single-line connection according to which electrode is touched.

The contributions of this paper are as follows:

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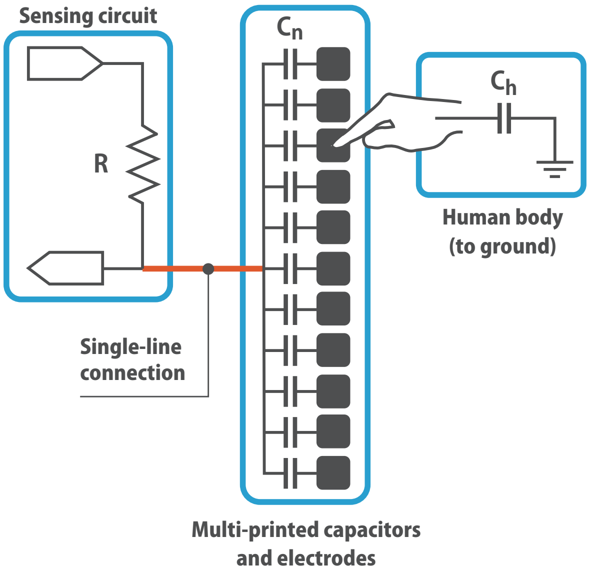

Figure 1. RootCap Concept.

1. We developed a touch sensing method that can detect touch to an electrode on a multi-electrode input surface with a single-line connection.
2. We developed a technique for creating a capacitor by printing silver nanoparticle ink on both sides of a sheet of paper, supporting designers in the creation of a multi-electrode input surface, on which each electrode has a unique capacitance.
3. We obtained high detection accuracy of touched electrodes and gestures on a multi-electrode input surface. Thus, we demonstrate the feasibility of this method for use in rapid prototyping.

RELATED WORK

Input Methods for Rapid Prototyping

Since it is important for designers to test usability of interactive products through rapid prototyping, many input methods for rapid prototyping have been researched; specifically, there has been intensive research on touch sensing methods. Touché [20] is a technology that adds touch sensitivity to electrically conductive objects. It observes impedance by attaching a conducting wire to the target object and imposing an electrical current; it detects how the object is touched by using machine learning, since the impedance changes depending on the way in which the object is touched. Touch & Activate [17] and Acoustruments [11] are methods that sense touch through sound. While their concept for touch detection are similar to that of Touché, it can add touch-sensitivity to objects without electrical conductivity, using sound instead. In contrast to these approaches, our method can even detect gestures by using multiple touch electrodes while our method uses dedicated touch electrodes.

Instant Inkjet Circuits [9] utilize home-use ink-jet printer to print circuits with silver nanoparticle ink on paper such as wires, resisters, and free-form electrodes. Karataş et al. [7] used this method to create multi-key controllers by printing a resister and switches. This printed circuit works as a voltage divider; when the user shorts any printed switch by touching it, the sensing circuit connected to the voltage divider can detect which printed switch was touched by observing the divided voltage. In contrast to this method, which requires a two-line connection between the voltage divider and the sensing circuit, our method uses a single-line connection.

Of the touch sensing method, a capacitive touch sensing [19, 2, 24, 5, 6] is well-studied. One merit of the capacitive sensing method is that it requires only a single-line connection between the sensing circuit and a touch electrode when the system has a single electrode.

There have been some studies based on the capacitive sensing method in which touch sensors were built using silver nanoparticle ink or print boards as touch-sensitive electrodes [9, 14, 4, 15, 16, 8]. For example, Instant Inkjet Circuits [9] printed a comb-like capacitor with silver nanoparticle ink to serve as a two-line connected touch sensor. Olberding et al. [14, 16, 15] attempted to use surfaces printed with silver nanoparticle or luminous ink in prototyping objects with touch sensitivity. Extension Sticker [8] extended touch sensitivity out of the capacitive touch screen by adding stripes printed with silver nanoparticle ink. By contrast, we focus on detecting touch to an electrode on a multi-electrode input surface using a single-line connection.

Touch Detection by a Single-line Connected Electrode

Detecting a touch and/or touch gestures using a single-line connection has also previously been explored by many researchers. Wimmer et al. [23] detected a touched point on a single conductive wire, by observing the reflection of the Time Domain Reflectometry (TDR) pulse caused by touch. Kawahara et al. [9] showed that silver nanoparticle ink can be used to print the Hilbert pattern in [23], which was then used as a touch electrode. While they used a complicated sensing process requiring a reflectometer or network analyzer, our method uses a simple sensing circuit and can detect a touched electrode by imposing unique capacitance on each one. Manabe et al. [12, 13] proposed a method to detect the number of fingers used to swipe, and their direction using two electrodes; they used a single-line connection for their capacitive sensing method. While our method also uses a single-line connection, it can detect a touched electrode among multi-electrodes, which can be used to detect touch gestures such as swipes. Takada et al. [22] extended Manabe's method [12, 13] and devised a pattern of electrodes, that can detect five touch gestures: a tap and swipes in four directions. The pattern was connected with a single-line connection to a sensing circuit. In contrast, our method can detect one touched electrode among multi-electrodes.

Conductive Ink Capacitors

The idea of using conductive ink, including silver nanoparticle ink, to form a capacitor is not new. There was a comb-like capacitor that was formed by printing silver nanoparticle ink on one side of a paper [9]. In contrast to the comb-like capacitor, whose shape and layout are limited, our method gives designers a greater degree of freedom in shape design.

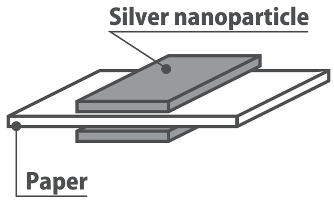

Figure 2. Structure of the double-printed capacitor.

Ta et al. [21] printed silver nanoparticle ink on both sides of a sheet of paper to form a multilayered circuit; Olberding et al. [16] printed conductive ink in multiple layers to form a capacitive touch sensor using screen-printing. We simply print silver nanoparticle ink on both sides of a sheet of paper to form a capacitor.

ROOTCAP

RootCap is a capacitive touch sensing method that can detect a touch on a multi-electrode input surface while maintaining the characteristics of a single-line connection as illustrated in Figure 1. This is realized by imposing unique capacitance on each electrode (including the capacitor connected to the touch electrode) branched from the single-line connection. As a result, when the user touches an electrode, a specific capacitance is observed via the single-line connection in accordance with the electrode that was touched. Therefore, by observing the capacitance of the single-line connection using a sensing circuit (the left side of Figure 1), the touched electrode can be detected. Moreover, supporting designers in the creation of a multi-electrode input surface, each of electrode has unique capacitance, is an important issue. To this end, we present a technique for creating a capacitor by printing silver nanoparticle ink on both sides of a sheet of paper, as illustrated in Figure 2. We call this capacitor a *double-printed capacitor*. Note that designers can also easily print a touch electrode with silver nanoparticle ink, including the wire that connects it with a double-printed capacitor.

In this section, we describe the double-printed capacitor, a touch sensing circuit that measures capacitance, and an example application using RootCap.

The Double-Printed Capacitor

A double-printed capacitor is structured as shown in Figure 2. The sheet of paper serves as a dielectric; the silver nanoparticle ink printed on both sides of the paper serves as a conductor. Conductors can be printed with silver nanoparticle ink as filled-in shapes at the same position on both sides of the paper. Thus, their capacitance can be designed by changing the area of each shapes.

In contrast to the comb-like capacitor [9], our method gives designers a greater degree of freedom in designing capacitor shape, such as the ones shown in Figure 3. Moreover, printing technology using silver nanoparticle ink is now being used in rapid prototyping of circuits on paper, including components such as wires, registers, free-form electrodes, and even touch sensors [9, 7, 14, 4, 15, 16, 8]. Therefore, our double-printed capacitors can be used in combination with such technologies, supporting designers in rapidly prototyping more complex circuits.

Figure 3. Free-form double-printed capacitors.

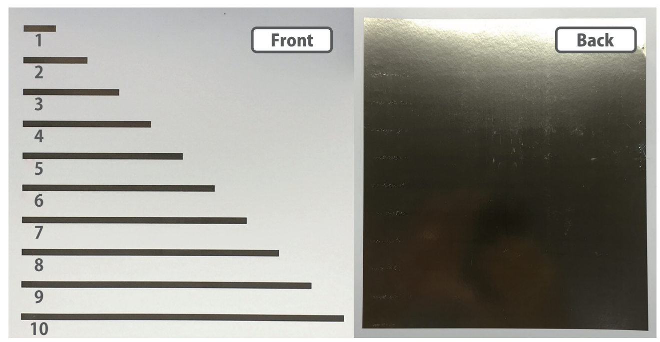

Figure 4. Tested double-printed capacitors.

Apparatus and Materials

In this implementation, we used a Brother DCP-J525N printer, Mitsubishi Paper Mills Limited NBSIJ-MU01 silver nanoparticle ink, and KOKUYO KJ-G23A4-30 paper.

Measuring Capacitance

We tested the relationship between the printed area of a double-printed capacitor and its capacitance. We created capacitors of 10 different sizes (labeled with IDs 1–10 from top to bottom), as shown in Figure 4, whose areas were $100\,\mathrm{mm}^2$, $200\,\mathrm{mm}^2, \cdots, 1000\,\mathrm{mm}^2$. We measured each capacitance by using an LCR meter (DER EE LCR METER DE-5000). Figure 5 shows the result. The horizontal axis represents each capacitor's ID; the vertical axis represents capacitance. This result shows that area and capacitance have a linear relationship, which is consistent with the theory that the capacitance of a parallel plate capacitor is proportional to the plate's area.

Design Guideline

Since our method detects a touched electrode by observing the capacitance of the single-line connection, and capacitance is measured as a function of the capacitor's charging time (i.e., the time required for the capacitor to become charged),

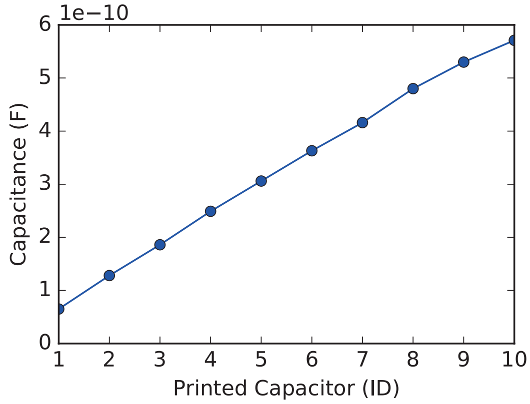

Figure 5. Capacitance of each strip.

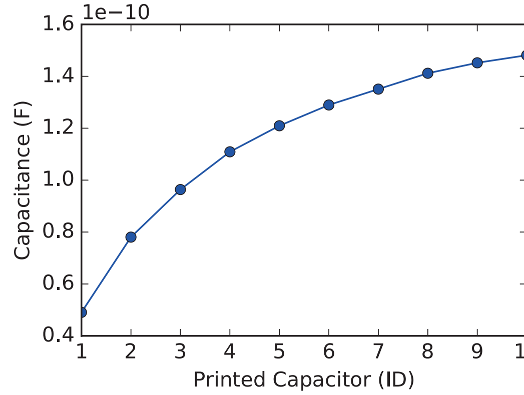

Figure 7. Combined capacitance of C_n and C_h

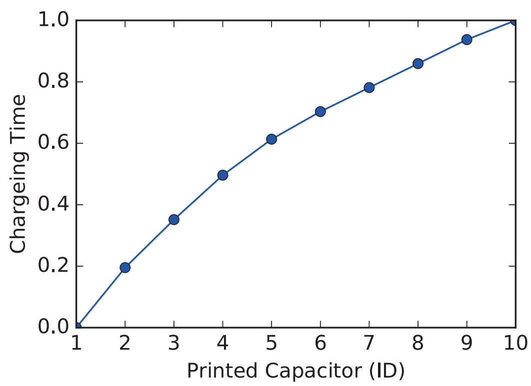

Figure 6. Charging time for each capacitor measured by our circuit.

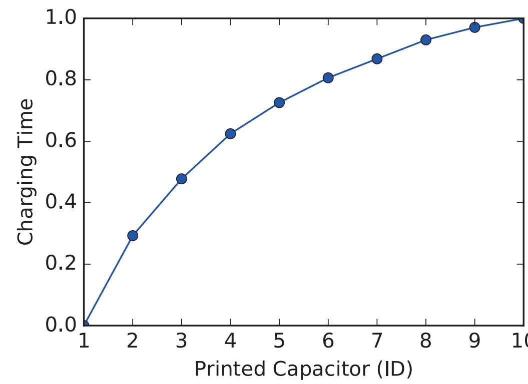

Figure 8. Theoretical charging time.

the difference in charging times should be large enough between the touch electrodes to avoid noise, which affects the design of touch electrodes.

First, we observed charging time, using a sensing circuit shown in Figure 1, when touching the double-printed capacitors one-by-one. The result is shown in Figure 6. The horizontal axis represents each capacitor's ID; the vertical axis represents measured charging time, which is normalized for later comparison.

On the other hand, the theoretical charging time t of a capacitor with the capacitance C is

$$t = -RCln(1 - \frac{V_t}{V_0}). \tag{1}$$

In this equation, R is the resistance in Figure 1; V_t is a threshold voltage; V_0 is the voltage applied to the capacitor. Since the logarithm term is constant, Equation 1 can be simplified by defining $A = ln(1 - Vt/V0)$ as

$$t = -ARC. \tag{2}$$

By transforming Equation 2, the observed capacitance can be represented as

$$C = -\frac{t}{AR}. \tag{3}$$

Note that the observed capacitance is the combined capacitance of C_n (the capacitance of the double-printed capacitor) and C_h (the users body capacitance). Because C_n and C_h are connected serially as illustrated in Figure 1, C is

$$C = \frac{C_n C_h}{C_h + C_n}. \tag{4}$$

To understand the relationship between C_n of a touch electrode and the observed capacitance (the charging time) in the single-line connection (the center panel in Figure 1) in conjunction with C_h, we first measured C_h with our touch-sensing circuit (the left side of Figure 1). When one of the authors touched the single-line connection having inserting neither any electrodes nor a capacitor, t was $3\,\mu$s. Using Equation 1, C_h was calculated as $221\,\mathrm{pF}$ with $R = 10\,\mathrm{k}\Omega$, $V_t = 2.5\,\mathrm{V}$, and $V_0 = 3.3\,\mathrm{V}$ (we defined $R = 10\,\mathrm{k}\Omega$ and $V_t = 2.5\,\mathrm{V}$ empirically). This result matches [3] and [18], which measured human body capacitance. From this result, we calculated the combined capacitance C of each C_n (measured with an LCR meter) and C_h (i.e., $221\,\mathrm{pF}$) using Equation 4 and plotted the result in Figure 7. The horizontal axis represents each capacitor's ID; the vertical axis represents the combined capacitance. We also calculated the theoretical charging time using Equation 2 with $R = 10\,\mathrm{k}\Omega$ and the calculated combined capacitance in Figure 7, and plotted the result in Figure 8. The horizontal axis represents each capacitor's ID; the vertical axis represents theoretical charging time, which is normalized for comparison with Figure 6. When comparing Figure 8 with Figure 6, we observe that the theo-

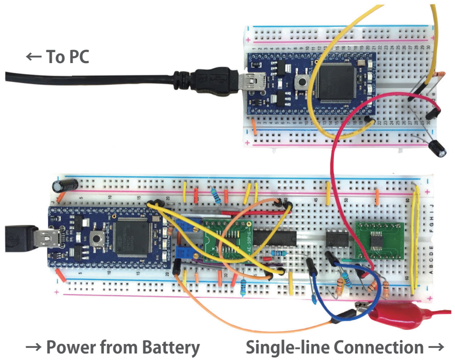

Figure 9. Touch sensing circuit (prototype).

retical and measured charging times match well. Therefore, Equation 1 can be used as a model to estimate capacitance from the charging time measured with the sensing circuit in Figure 1.

For further analysis, we then formulate $C_n = aS$ where a is a constant that depends on the paper and ink; S is the area of a double-printed capacitor. Inserting this into Equation 1 yields

$$t = -AR\frac{aSC_h}{C_h + aS}. \tag{5}$$

Equation 5 shows that as the area of a double-printed capacitor grows, the growth in charging time gradually slows down. This observation also appears in Figures 6 and 8, in which the growth rate of the charging time converges around double-printed capacitor 10, whose area was $1000\,\mathrm{mm}^2$. Therefore, in this implementation, with $R = 10\,\mathrm{k}\Omega$, we recommend that the printed capacitor's area should not exceed $1000\,\mathrm{mm}^2$, and that the gap between capacitor of this area and others should be as large as possible. Additionally, the upper limit of the area is also affected by R. Therefore, if designers want to create a larger printed capacitor, they should use smaller R, and vice versa. Besides, there is no limitations when designing touch electrodes, because there is no limitations in the area of the touch electrode connected to the printed capacitor part.

Touch Sensing Circuit

We implemented a touch sensing circuit (Figure 9) based on a capacitive sensing method described in [12]. Its simplified circuit diagram is depicted in Figure 10. Figure 9 contains two sets of the circuit depicted in Figure 10 (excluding a wire for touch electrodes and one for sensor output) for noise reduction. Among some approaches to measure capacitance or to detect the alteration of capacitance, such as measuring the charging time or observing the resonant frequency, we adopted a simple approach which measures the charging time. While most of the following logic can be implemented by programming a microcomputer, we implemented it via hardware, which enabled rapid capacitance measurement.

To measure the charging time, we need two rectangular pulse signals: one for charging the touch electrode (Pulse A), which is deformed when the electrode is touched, and the other for measuring the charging time (Pulse B). We also measure the

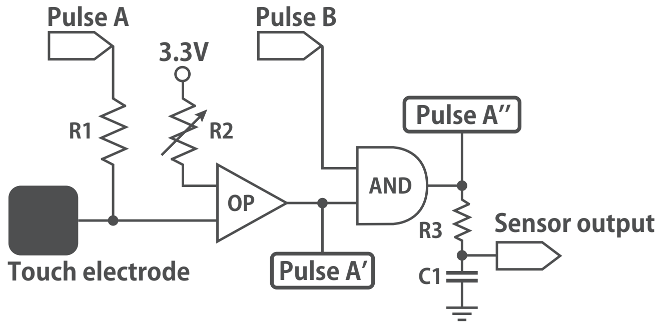

Figure 10. Touch sensing circuit.

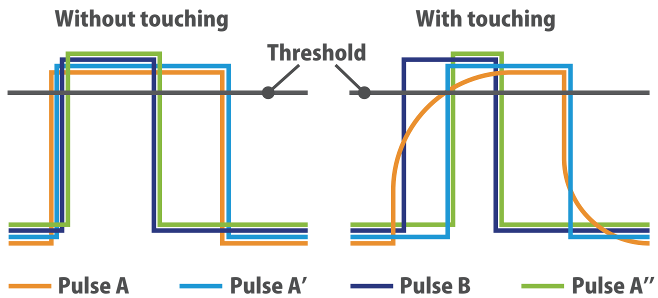

Figure 11. Pulses for sensing.

discharging time for noise reduction, which can be measured with the same mechanism for charging. Therefore, we use four pulse signals as shown in Figure 11 for sensing. Below are the methods by which these components allow us to acquire the charging time. To charge the touch electrode, we use Pulse A, a pulse with a duty cycle 1/2. We arrange Pulse B so that its rising edge matches that of Pulse A and its falling edge does not exceed that of Pulse A. We also determine a threshold voltage (R2). When Pulse A passes R2, we determine the time as the finish time of charging. When the touch electrode is touched, Pulse A rises slowly (the right in Figure 11) because the human body is also charged. Thus, it takes more time for Pulse A to reach R2 when touched, compared to when not touched. Therefore, comparing the voltage of Pulse A and R2 with a comparator (OP in Figure 10) generates a signal (Pulse A') which is HI while Pulse A is passing R2. Since the falling edge of Pulse A leans to the right when touched, passing Pulse A and Pulse B to an AND gate (AND in Figure 10) generates Pulse A which becomes wide when not touched and narrow when touched. A low-pass filter (R3 and C1 in Figure 10) converts the duration of Pulse A to its moving average (i.e., the longer the duration is, the higher the voltage is, and vice versa). Thus, by using an ADC, we can obtain the charging time as a discrete one dimensional value.

We used the pseudo-differential measurement [1] also used in [12] to decrease noises such as the one from a commercial power supply. Generally, this method decrease noise by summing the noisy signal (i.e., the signal for measuring the charging time in our case) and a signal with the reverse-phased noise. For the reverse-phased noise, we used the signal for measuring discharge time, which is acquired by the same mechanism as charging time. Figure 9 contains two

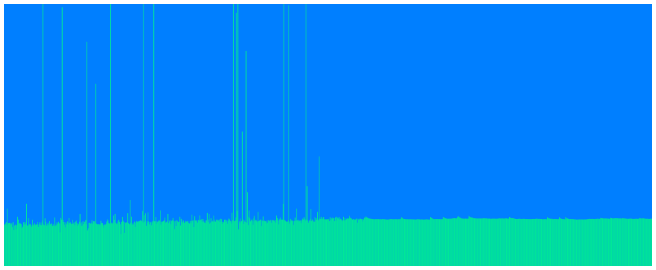

Figure 12. Figure 12. Effect of low-pass filters by both hardware and software; horizontal axis: time; vertical axis: sensor value where length of blue represents charging time. Half left: sensor value with low-pass filters. Half right: sensor value without low-pass filters.

sets of the circuit in Figure 10 (excluding a touch electrode and sensor output)—one each for acquiring charging and discharge times—to implement the pseudo-differential.

In addition, we added some contrivances to measure the charging time stably. First, we enabled it to adjust the sensitivity of the capacitance sensor value by allowing the threshold to vary (R2 in Figure 10), which determines the charging completion time of pulse A. For example, to obtain a large difference of charging time when the difference of charging time is so small between touch electrodes causing detection errors, the threshold for charging should be adjusted larger and the one for discharging should be adjusted smaller. Next, we added low-pass filters by both hardware and software to decrease the noise that could not be absorbed by pseudo-differential measurement. The half left of Figure 12 shows the measured charging time without this noise reduction; the half right shows one with this noise reduction. Third, we omitted a voltage follower placed near the electrode, which was used in [12]. This omission was due to large voltage drop, which was an adverse effect for observing detailed capacitance variations. Instead, we attached ferrite clamps to the single-line connection and power line to decrease the noise. Moreover, this circuit can be driven by a commercial power supply or bus power from a PC, but when a clear signal is required, a battery should be used.

Example Application

To evaluate the detection accuracy of multiple electrodes on a single-line connection, we developed an evaluation application: a numeric keypad. The keypad is composed of touch electrodes connected with 10 double-printed capacitors (Figure 13), a touch-sensing circuit (Figure 9), and PC software for detection (Figure 14).

Printed Numeric Keypad

The numeric keypad we developed (Figure 13) consists of two parts: the capacitor (top) and the touch electrode (bottom).

The capacitor is formed by printing silver nanoparticles onto both sides of a sheet of paper. The front surface is arranged from 10 differently sized parts, each of which is U-shaped in order to increase the printed area. A single rectangle that covers the entire surface of the capacitor component is printed on the back surface of the paper; this forms 10 double-printed

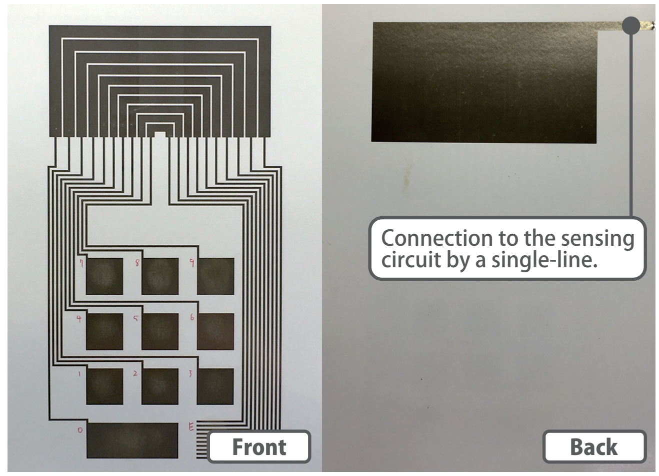

Figure 13. Numeric keypad.

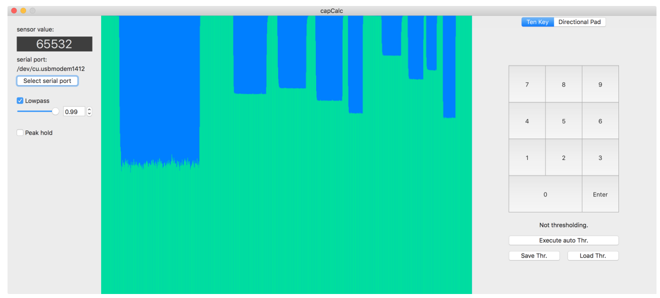

Figure 14. PC software for detection.

capacitors with the 10 areas on the front surface. A single-line connection is connected from the back surface to the sensing circuit.

The touch electrode part has electrodes connected to the double-printed capacitors, each of which serves as a numeric key. In addition to the 10 numeric keys, we designed the enter key as a stripe pattern; when the user touches the enter key, all of the double-printed capacitors are touched at once, resulting in the largest capacitance observed on the single-line connection. This design shows a possibility where the designers can increase touch electrodes while reducing the number of double-printed capacitors.

PC software for detection

We implemented PC-based software (Figure 14) that detects the numeric key touched and shows the result.

The software has three display areas. The area on the left displays the sensor value, and provides a GUI for choosing the serial port and controlling the software low-pass filter. The center area plots the sensor values. The horizontal axis represents time; the vertical axis represents the sensor value. The plot colored green represents sensor value. The smaller the sensor value, the larger the capacitance when touched. The area on the right displays the virtual keys.

The software uses the sensor values, which are sent to the PC via USB from the touch-sensing circuit, to detect the numeric key (i.e., the touched electrode) with a threshold-based ap-

Detected

Touched

	none	Enter	9	8	7	6	5	4	3	2	1	0
none	1											
Enter		0.96										0.04
9	0.08		0.92									
8			0.04	0.96								
7					1							
6						1						
5							1					
4							0.04	0.96				
3									1			
2										1		
1											0.88	0.13
0												1

Figure 15. Multi-electrode numeric keypad detection accuracy.

proach. Therefore, the software requires an initial calibration: the user touches each electrode in order before using the numeric keypad. The software automatically binds the touched electrode to the corresponding virtual key using this sensor value. The calibration is completed when the user touches all of the electrodes. After the calibration, when the user touches an electrode, the software highlights the bound virtual key on the display.

EVALUATION

Because touch gestures can be categorized into discrete and continuous ones, we conducted two experiments. The first one is for evaluating the detection accuracy of touches with multiple-electrodes, as an example of a discrete gesture. The second one is for evaluating the detection accuracy of vertical and horizontal swipes as an example of a continuous gesture.

Multi-electrode Detection

We carried out an experiment to evaluate the detection accuracy of touch electrodes connected by a single-line connection. In this evaluation, we used the touch electrode shown in Figure 13. This is a numeric keypad with 11 keys, which are numbers from 0 to 9 and Enter. Enter has the largest capacitance, 0 has the second largest, and 9 has the smallest. Each of the participants (8 persons whose ages ranged from 21 to 24) touched each electrode in order before using the numeric key for calibration. Next, the participants touched the electrodes in order to evaluate the systems accuracy. Each key was touched 3 times by a participant; all keys were touched 264 times by the 8 participants. We recorded the keys touched and whether the software responded to the correct key to evaluate detection accuracy.

The result of this experiment is shown in Figure 15 as a confusion matrix. The vertical axis represents the key which the participant actually touched; the horizontal axis represents the key which the software detected. The average detection accuracy was 97.2%. The accuracy in detecting the key corresponding to the number 1 was the lowest. Key 1 is third-largest in capacitance size, at $530\,\mathrm{pF}$. In referring to the design guideline, we know that it is difficult to observe capacitance size near the capacitor. From Equation 4, the combined capacitance when touching Key 1 is $156\,\mathrm{pF}$ which is calculated by substituting $C_n = 530\,\mathrm{pF}$ and $C_h = 222\,\mathrm{pF}$ to Equation 4. On the other hand, from Figure 7 which shows the combined capacitance, we can observe that the growth rate of the combined capacitance converges stronger at around $140\,\mathrm{pF}$, making it difficult to observe the change in the combined capacitance around Key 1, thus decreasing detection accuracy.

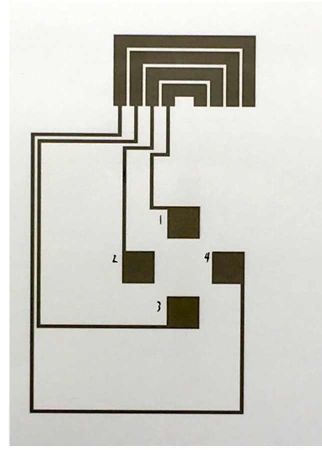

Figure 16. Gesture pad.

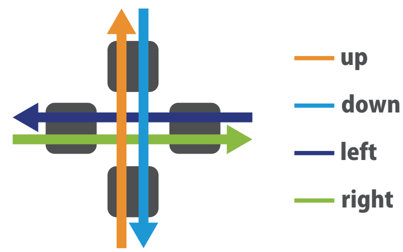

Figure 17. Detection of 4 touch gestures: up, down, left, right swipes.

Gesture Detection

We conducted an experiment to detect 4 touch gestures: up, down, left, right swipes. The design of the electrode is shown in Figure 16, and has 4 types of printed capacitor with electrodes connected to each one. The participants touched the electrode shown in (Figure 17), and can input 4 distinct swipe gestures. In each swipe gesture, two electrodes are touched. As the result, the sensor values for each gesture appear in Figure 18. In this signal, gestures can be detected from the difference in the two continuing signals that are emitted from a single gesture. The software for this experiment shows the detected gesture. The participant in this part of the experiment was 24 years old. The participant performed 4 gestures in a random order 10 times for a single trial. Ten trials were carried out in total, thus each gesture was input 100 times.

The result of this experiment is shown in Figure 19 as a confusion matrix. The vertical axis represents the gesture that the participant actually performed; the horizontal axis represents the gesture that the software detected. Average accuracy of detection was 96.8%. From the result, we observed that the up and left gestures tended to be confused with each other. This would occur because the sensor values of the up and left

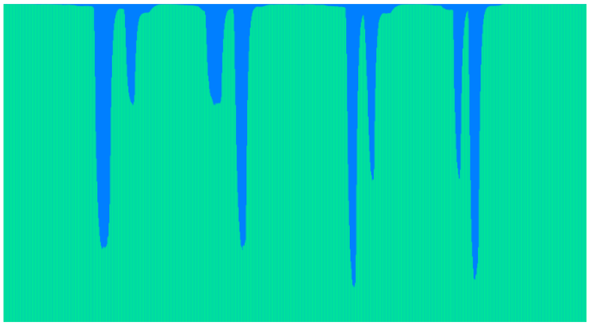

Figure 18. Sensor values for 4 gestures. From from left to right, the gesture directions are up, down, left, and right.

Gestured \ Detected	up	down	left	right
up	0.89	0.01	0.09	0.01
down		1		
left	0.02		0.98	
right				1

Figure 19. Accuracy of gesture detection.

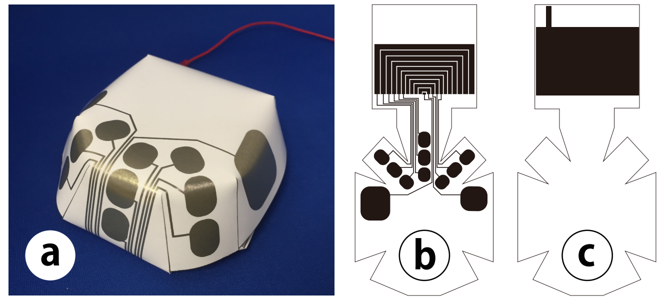

Figure 20. Ergonomic keypad. a) Overview of the ergonomic keypad with a single-line connection. b) Front side. c) Bottom side.

Figure 21. Interactive Christmas ornament.

gestures tended to be similar and because it was harder to slide the finger upwards, which made the sensor values unstable.

EXAMPLES OF PROTOTYPING

Ergonomic Keypad

By using the numeric keypad which we used for evaluation, the designers can design a keypad with flat, curved, or flexible surface. We show the example of ergonomic keypad on Figure 20. As this figure, designers can hide printed capacitors inside of the prototype and only single-line wire to the sensing circuit should be connected. This allows designers to raise the degree of freedom for the shape and layout of touch electrodes and whole shape of the prototype.

Slider

A slider can be implemented by lining up stripes (i.e., electrodes) with different capacitance. When sliding the finger over the stripes, the finger rides on several stripes. This results in continuous bumpy waves in sensor values, which denote the direction and length of the slide. We can also recognize where the finger stopped.

Interactive Christmas Ornament

We can use our method to create simple controllers made of paper with only a single-line connection, which we can use as decorations. By touching the star of the ornament shown in Figure 21, the user can control the light. For example, by touching the top edge of the star, all the lights are turned on. The two edges on the bottom are controllers that switch between white and red lights.

Control Panel Prototype of Car or Consumer Electronics

When developing a UI for consumer electronics and large touch panels for cars, it is necessary to iterate the design many times. Additionally, panels with free curved surfaces have begun to be marketed, and it is likely that such surfaces will become more prevalent at technology improves. Rapid prototyping of touch interfaces on such operation panels with our method, which can create flexible shaped touch surfaces any where with a single-line, will contribute to design efficiency.

Touch Interactive Architecture Prototype

Our method could also be used in the field of architecture. For example, when creating complex architecture models from styrene or paper board, the designers can assemble and implement touch-operating panels for multiple illuminations with our method. Such models could reduce the cost of wiring, connecting and, and designing operating panels.

DISCUSSION AND FUTURE WORK

In this paper, we discussed a limit the resolution of detection. Thereby, we presented a design guideline for the maximum limit of the area of a double-printed capacitor. Therefore, our immediate future work is to explore further design guidelines to help the designers determine the number and areas of double-printed capacitors.

There are also possibilities on reducing the implementation area in gesture detection, because only requires 3 types of capacitors in minimum to detect 6 directions gestures as shown in Figure 22. By extending our method, it may also be feasible to solve the electrode margin restrictions shown in [22].

Furthermore, in a pilot study, our method could detect gestures such as hover, double taps, and triple taps with each electrode. Since the design of our sensing circuit is simple, we are planning to miniaturize and package this. We also can imagine other applications. For example, our method makes it possible to implement a touch panel with high-speed responses by decreasing the number of connections and multiplexer processes. As another future work, we are planning to devise the system for simultaneous multi-touch.

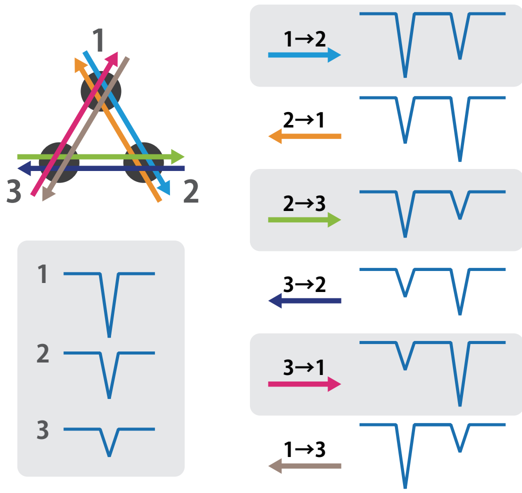

Figure 22. Six touch gestures with 3 types of capacitors.

CONCLUSIONS

In this paper, we present RootCap, a capacitive touch sensing method that can detect a touch on a multi-electrode input surface while maintaining the characteristics of a single-line connection, as illustrated in Figure 1. From the preliminary research, we were able to derive the relational expression of capacitance, area of printed capacitor, and the charging time when touched by human. For a single-line connection, we set a design guideline limiting the largest area to $1000\,\mathrm{mm}^2$, knowing that 10 stages were the most useful number of electrodes. In addition, we did an experiment to determine whether we could detect 11 stages of keys correctly with only a single-line connection. As a result, the total detection accuracy for our numeric keypad was 97.2% We also did an experiment to understand if we could detect 4 gestures by using a 4 staged single-line connection. We also carried out an experiment to confirm whether we could detect 4 gestures using a 4-stage single-line connection. As a result, the total detection accuracy of gestures was 96.8%. Therefore, we were able to reduce connections in order to rapidly create touch sensors, and were also able to reduce the implementation area of touch sensors which could detect multiple types of input. Moreover, we show a technique call for creating a capacitor, which we call a double-printed capacitor, by printing silver nanoparticle ink on both sides of a sheet of paper. This technique supports designers in the creation of a multi-electrode input surface, on which each electrode has a unique capacitance with a greater degree of freedom in shape design. RootCap meets the requirements of touch input methods for rapid prototyping: the number of connections between the sensing circuit and touch electrodes is decreased while the number of available touch electrode is increased, and raising the degree of freedom for the shape and layout of touch electrodes. As a result, we were able to demonstrate the feasibility of our method for use in rapid prototyping.

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