Ohmic-Touch: Extending Touch Interaction by Indirect Touch through Resistive Objects

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ABSTRACT
When an object is interposed between a touch surface and a finger/touch pen, the change in impedance caused by the object can be measured by the driver software. This phenomenon has been used to develop new interaction techniques. Unlike previous works that focused on the capacitance component in impedance, Ohmic-Touch enhances touch input modality by sensing resistance. Using 3D printers or inkjet printers with conductive materials and off-the-shelf electronic components/sensors, resistance is easily and precisely controllable. We implement mechanisms on touch surfaces based on the electrical resistance of the object: for example, to sense the touching position on an interposed object, to identify each object, and to sense light, force, or temperature by using resistors and sensors. Additionally, we conduct experimental studies that demonstrate that our technology has a recognition accuracy of resistance value of 97%.

ACM Classification Keywords
H.5.2. Information Interfaces and Presentation (e.g. HCI): User Interfaces Input Devices and Strategies.

Author Keywords
Indirect Touch; Capacitive Touch Surface;
Tangible User Interface; Digital Fabrication.

INTRODUCTION AND RELATED WORK
In recent years, capacitive touch surfaces such as those used in trackpads, smartphones, tablet PCs and smart watches have become widespread and are currently the most popular user input method for such devices. Although these modern touch surfaces were originally designed to detect multi-touch by fingers, they show the promising possibility of expanding input modality. To increase the expressiveness of touch inputs, a tremendous body of research has focused on input techniques that use passive tangible objects on a touch surface. Some of this research has shown that the capacitive touch surface can be utilized to identify tangible objects itself or to recognize the x-y location and the rotation angle of the object [17, 7, 11, 31].

Some approaches allow for touch inputs on the surface of the object itself [3, 15, 14, 20]. In ZebraWidgets [3], Extension-Sticker [14] and 3D Printed Physical Interfaces [15], when the user changes the touch position on the object, the touch position on the surface is changed accordingly. By using this, [3] and [14] provide swiping or pinching operations and [15] provides two-dimensional pointing. One of the applications of GaussBrick [20] allows a swiping operation on the conductive part of the object. Although previous approaches expanded the input vocabulary for capacitive touch surfaces, the input modality is still limited because they can only detect discrete states for each touch point, i.e., touching or non-touching state at specific locations on the conductive material.

More recently, some tangible objects have provided a modality of continuous input for touch surfaces. Flexibles [26] are 3D-printed objects embedded with a conductive material inside a flexible insulator material. Flexibles recognize the deformations such as pressing, squeezing, and bending for tangible interactions by detecting the change in capacitance that occurs when the distance between the conductive material and the touch surface or fingers changes. This approach is promising, but it is still difficult to design a tangible object that can produce appropriate changes in capacitance for certain user actions.

In addition to capacitance, resistance can also be detected by capacitive touch surfaces. In general, controlling resistance is easy, because a wide range of precise and tiny resistors are easy to fabricated at low cost. Many adjustable resistors (i.e., variable resistors or potentiometers) are available off-the-shelf and are used inside input devices such as rotary dials, sliders, foot pedals, and joysticks. Moreover, there are low-cost and battery-less sensors that return the amount of light, temperature, pressure, bending, and sound detected as a resistance value. These electronic components and sensors can be used to enhance touch surface interactions by embedding tangible objects that touch the sensing surface.

In this paper, we propose a novel indirect touch technique called "Ohmic-Touch" that provides continuous touch input modality for off-the-shelf capacitive touch surfaces. In contrast to Flexibles [26] that uses capacitance, we focus on the electric resistance of tangible objects. Ohmic-Touch recognizes the touch location on a tangible object surface, identifies

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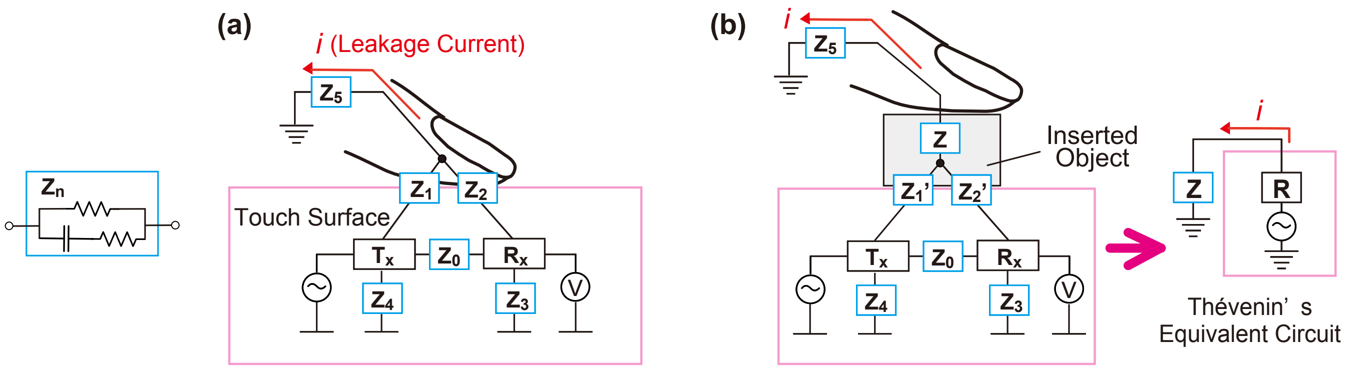

Figure 1. Equivalent circuit of capacitive touch surfaces. (a) Conventional touch; (b) Indirect touch through an object. It can be replaced with an equivalent circuit based on Thévenin's theorem.

the objects being used, and senses rotation, pressure, temperature, light, and bending. We have tested the feasibility of our technique and prototype applications.

OHMIC-TOUCH

This section describes the principles of touch detection on a modern (mutual capacitance) capacitive touch surface and then introduces the operating principles of Ohmic-Touch.

Touch Detection Principle on a Capacitive Touch Surface

A capacitive touch surface has a structure in which two types of transparent linear electrodes are arranged in a lattice shape [23]. The first type is the transmission electrode group and the other is the receiving electrode group; they are orthogonal to each other. Figure 1 (a) shows the equivalent circuit at the intersection of the transmission electrode (T_x) and the receiving electrode (R_x). The blue colored blocks denoted as Z_n are the impedance of the substance around the touch surface. They can be represented as an equivalent circuit consisting of resistors and capacitors. The electrodes T_x and R_x are grounded via Z_4 and Z_3 and are connected to each other by Z_0. When the transmission electrode T_x is excited by a high-frequency signal, a receiving electrode R_x receives this signal through the impedance network. When a conductive and grounded object is not in contact with the electrode intersection covered by insulator materials such as a glass, the electrical coupling of T_x and R_x is Z_0, resulting in the signal being transmitted from T_x to R_x through Z_0. On the other hand, when a conductive and grounded object, such as a finger, approaches the electrode intersection, the object becomes electrically connected to T_x and R_x via Z_1 and Z_2. Simultaneously, the object is grounded via the impedance of the human body, Z_5. As a result, a part of the signal from T_x leaks to the ground (i), and the signal received by R_x is attenuated. The touch driver of a touch surface determines the touching and non-touching states depending on whether the attenuation amount exceeds a constant threshold.

Detecting Impedance of the Touching Object

The amount of current i being shunted to the ground by a touch depends on the impedance on a path to the touch. Therefore, as shown in Fig. 1 (b), when an object is interposed between the touch surface and a grounded conductor, the detected signal differs from the signal detected in the case of a direct touch. In addition, the signal changes depending on the electrical characteristics of the intervening object such as the dielectric constant and resistivity. In general, any circuit that combines elements with electromotive forces and impedance can be replaced with an equivalent circuit based on Thévenin's theorem [21], and it can be simplified to a circuit having an internal impedance and an electromotive force. Therefore, assuming that the load of the impedance Z is connected to the power supply of electromotive force E and the internal impedance R, the flow current i can be expressed as

$$i = \frac{E}{(R+Z)} \quad (1)$$

Using Eq. (1), Z can be estimated by the current i or by a certain value that is proportional to i. The mechanism for acquiring values in correlation with i (hereafter referred to as "leakage current") is available in the operating systems of consumer devices such as Android or macOS. It is widely used in HCI research for measuring the capacitance component of impedance [26, 10, 8, 18, 30].

Interaction using Resistance

As mentioned in the related work section, several interaction techniques that use the change in the impedance Z as the input have been proposed. Previous studies mainly utilized the change in the capacitance component of the impedance Z. However, resistance also contributes to the leakage current i, as shown in Fig. 1. The proposed Ohmic-Touch method focuses on the electrical resistance component of the impedance Z. The change in the resistance value caused by the user is utilized for the interaction on the touch surface.

The prototyping of tangible objects with specific resistance distributions has become relatively easy owing to modern fabrication tools and applications [25, 29, 24]. A 3D printer can be used to create an object with a combination of conductive and insulating filaments [12, 19]. More recently, an integration method with 3D printed objects and electrical components circuit has been proposed [27]. A domestic ink-jet printer with conductive ink can be used to create a film having a conductive pattern [16, 13, 9]. The tangible objects used in Ohmic-Touch can also be prototyped by these tools and applications. In addition to the insulating and conductive parts, the tangible objects have electrodes at the bottom to contact the touch surface. Passive electronic circuits can be included in these objects. We can use electronic circuits with conductive wires and resistor components including fixed resistors, rotary or sliding variable resistors, and potentiometers. Sliding or rotating knob mechanisms that are commonly used in continuous adjustment are easily implemented using one of these electronic components. Battery-less sensors that return resistance values can also be used such as, light sensors (LDR or CdS cells), temperature sensors (thermistors), pressure sensors, flex sensors, angle sensors (potentiometers), and sound or vibration sensors (carbon microphones). When an Ohmic-Touch object with distributed resistance is placed on a touch surface, the resulting resistance is proportional to the distance from the touching electrode. In this case, the user's touch position on the surface of the object can be estimated from Z. In the case where an electronic circuit is included in an Ohmic-Touch object, a change in the resistance value caused by the user, such as rotating or sliding a knob, pressing, heating, or lighting, can also be estimated from Z.

FEASIBILITY STUDY

A feasibility study was carried out to confirm the impedance change by the following factors.

1. The size of the contact area of an intervening object and a touch surface
2. The resistance value of the intervening object
3. The touch location on a touch surface

Experimental Setup

We used a 13 inch MacBook Pro (OS X 10.11, trackpad: 105 × 75 mm). An investigation application was implemented using C++, openFrameworks and MultitouchSupport.framework. We utilized the "size" property of MultitouchSupport.framework that is in correlation with leakage current. We recorded the touch location and the leakage current measured by the framework. All investigations were conducted at a room temperature of 26 °C to 28 °C. To investigate (1) and (2), we prepared a touch pen object connected with 15 kΩ resistors connected in series along the length of the pen, starting at 15 kΩ, then increasing to 135 kΩ, at 15 kΩ intervals (Fig. 2). This object has touch points at the point where the resistors connect to each other.

Effect of the Contact Area Size

The number of electrodes that react in the touch surface varies depending on the contact area size between the touch surface and the object. Thus we investigated the contact area size to obtain the stable leakage current.

With reference to the electrodes grid spacing estimation method indicated in [28], we measured the electrode grid spacing of the trackpad that is used for this study. We observed the transmission electrode T_x signal by connecting a probe of an oscilloscope to a 5 mm wide strip of aluminum foil that spanned across the touch surface. With this setup, we measured the duration of the signal from one transmission electrode and the duration of the complete scan through all transmission electrodes. Electrode pitch was then estimated by dividing the physical touch surface by the number of electrodes in the corresponding direction. Using this method, we found that the distance between electrodes is 7.5 mm or smaller. Therefore, we selected 6 mm (slightly smaller than the estimated spacing) as the minimum size for the study.

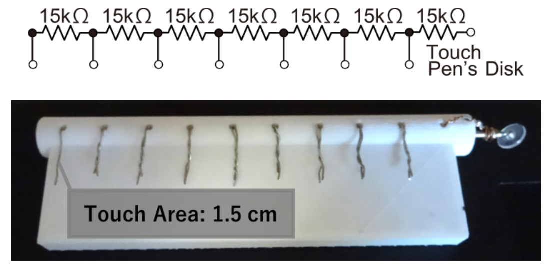

Figure 2. The touch pen object used for feasibility study. A series connected resistors are connected with the tip portion.

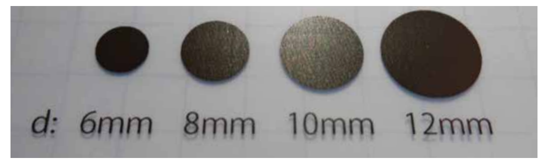

Figure 3. Circular disks with 6 mm, 8 mm, 10 mm and 12 mm diameter printed onto PET film using silver nano-ink.

As shown in Fig.3, we prepared pen tips of different sizes (6 mm, 8 mm, 10 mm and 12 mm diameter and printed onto PET film NB-TP-3GU100 [1] using silver nano-ink NBSIJ-MU01 [2] from Mitsubishi Paper Mill) to attach to the touch pen object. The touch operation was then carried out at the center of the trackpad. First, a ground connector is connected to the touch area closest to the pen tip thereby completing the circuit with a 15 kΩ resistor. Second, the connector is placed on the next touch area, thereby completing a circuit with a net 30 kΩ resistance. This process is then repeated for all the touch areas thereby increasing the net resistance value as the connector is moved farther away from the pen tip. A total of 360 trials were performed, which is the number of combinations of the nine resistance types, ten touches, and four pen tip sizes.

Figure 4 shows the average value of the measured leakage current for each contact area size and each resistance value along with the error as a standard deviation. The 6 mm and 8 mm diameter pen tips were able to detect the leakage current for all resistance values. The 10 mm and 12 mm diameter tips were able to detect the leakage current up to 105 kΩ and 90 kΩ, respectively. Because of the spacing between electrodes, the 10 mm and 12 mm tips were considered to react with multiple electrodes, resulting in an unstable state, i.e., large fluctuations in the measured leakage current. We conclude that for the trackpad used in this experiment, it would be preferable to use an object with a contact area of approximately 6 mm to 8 mm that are estimated to be the electrode grid spacing of the trackpad.

Effect of Resistance

To confirm how the resistance component of the impedance Z affect the leakage current, we conducted the experiment as

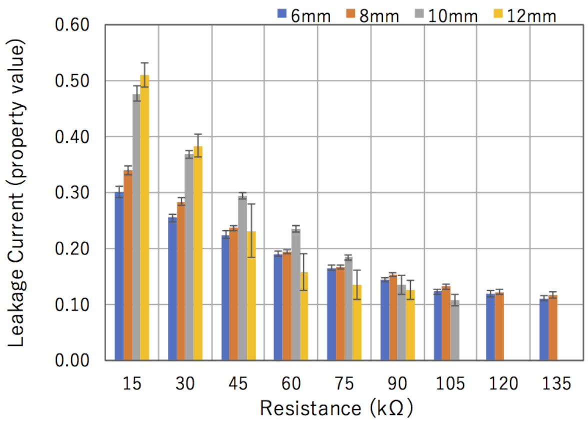

Figure 4. Mean leakage current with standard deviations to each contact area size.

follows. Ten participants (seven females and three males, aged 21 to 69, average:34.6, SD:17.9) were invited to participate in the study. While sitting, the participants placed an index finger on the touching area of the touch pen object (in order from low to high resistance value areas). The touch operation was performed at the center of the trackpad. From the results from the contact area investigation, we decided to use a 6 mm tip. A total of 270 trials were performed, which is the number of combinations of the nine resistance types, three touches, and ten participants.

Figure 5 shows the average value of the measured leakage current for each resistance value with the error as a standard deviation. The horizontal axis of the graph in Fig. 5 represents the impedance Z while the vertical axis represents the proportional leakage current i flowing to it. We computed a fitting a curve for data points using Eq. 1. The trackpad was able to detect all touch events for resistance values 15 kΩ to 135 kΩ. Eq. 1 shows that the maximum leakage current occurs at $Z = 0$, while it is reduced to half of the maximum current when $Z = R$, i.e., when the load impedance and internal impedance are equal. The curve fitting results in Fig. 5 indicates that maximum value of 0.36 at the y-intercept is reduced to half at 64 kΩ and at an internal impedance of 64 kΩ. We consider that the use of a resistance value of up to approximately the internal impedance value is appropriate because the change in the leakage current against resistance value becomes smaller when the resistance value becomes much greater than the internal impedance. At approximately the internal impedance value, the measured errors were 1.4 kΩ for 60 kΩ and 2.6 kΩ for 75 kΩ. Therefore, the resistance value can be estimated with a precision of approximately 97% below 75 kΩ across users.

Effect of Touch Location

We also investigated the effect of the touch location on the trackpad on the leakage current measurement. We used a commercially available touch pen with a tip disk[1]. Using the results from the contact area investigation, we decided to use

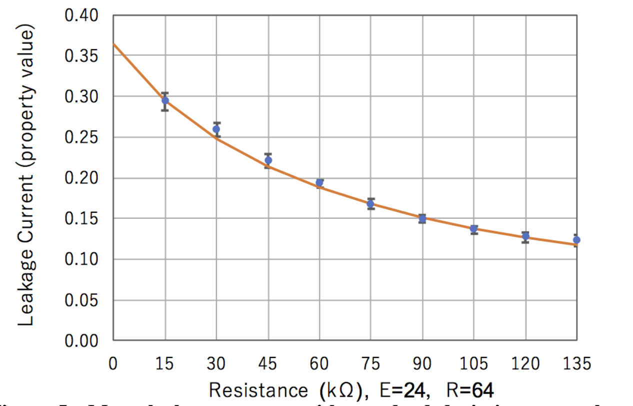

Figure 5. Mean leakage current with standard deviations to each resistance value. The mapping function computed by the least squares method is shown in orange curved line.

a 6 mm tip. We divided the trackpad into ten horizontal and seven vertical areas. The pen touched the center of each of the subdivided areas. In order to exclude the data in the proximity of the touch pen at the start and end of the touch, the touch was set to last for a total of 7 seconds wherein the data for the first and last seconds were excluded, thus resulting in five seconds of data being used. In subsequent experiments, the same procedure was performed. A total of 700 trials were performed, which is the number of combinations of the ten touches and the 70 divided areas.

Figure 6 shows the measured leakage currents with respect to the touch location. The area near the edge of the trackpad tended to have a slightly greater leakage as compared to that of the inner area. Near the edge of the trackpad, it is necessary to take into account this characteristic and to correct the value, especially for applications using the edge.

0.45	0.40	0.39	0.42	0.39	0.38	0.41	0.39	0.39	0.42
0.39	0.34	0.34	0.34	0.34	0.34	0.34	0.34	0.33	0.40
0.39	0.34	0.33	0.33	0.33	0.34	0.34	0.33	0.33	0.41
0.39	0.33	0.33	0.34	0.34	0.34	0.34	0.33	0.33	0.39
0.38	0.34	0.33	0.34	0.34	0.34	0.34	0.33	0.33	0.39
0.40	0.34	0.34	0.34	0.34	0.34	0.34	0.34	0.34	0.43
0.44	0.41	0.41	0.41	0.41	0.39	0.39	0.37	0.41	0.44

Trackpad: 105mm x 75mm

Figure 6. Mean leakage current at each touch location of the trackpad.

EXAMPLES OF APPLICATIONS

To demonstrate the practical feasibility, we developed examples of applications based on the feasibility study.

Touch Area Extension Interfaces

Figure 7(a) shows a touch bar printed by a fused deposition modeling (DFM) based 3D printer with a conductive ABS filament. The resistance value of the object with uniform resistivity is proportional to length. When the user touches the touch bar with one end of the touch bar placed on the trackpad, the application estimates the touch position from the change in the leakage current. This allows for one-dimensional parameter operations, such as scrolling or zooming operation, in

[1] Adonit Jot Pro 2.0, 6 mm tip diameter, a resistance of 10 Ω from the tip of the pen to the other end.

the touch area extended out of the touch surface. In previous works, the use of tangible objects [3, 14] or sheets [15] having a stripe or columnar arrangement of thin conductive materials was proposed to be used on touch surfaces. By swiping on the surface of the object or sheet, the user can scroll or zoom, among others. By using the proposed technique in this paper, it is possible to detect at the point on the line that is being touched by using the resistance value of the conductive material. By doing so, the dimension of the interaction region can be increased by one. For example, as shown in Fig. 7(b), a plate with a striped conductive pattern printed with silver nanoink such as that in ExtensionSticker [14] can be expanded to a two-dimensional input area for pointing.

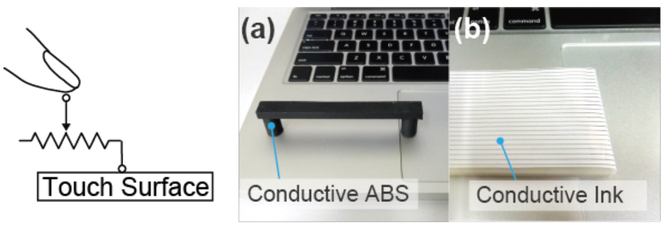

Figure 7. (a) 1-dimensional touch bar with conductive ABS (surface resitivity $10^3\Omega$ –$10^5\Omega$/ sq); (b) 2-dimensional touch plate with conductive ink (surface resitivity 0.2Ω/ sq).

Other examples are shown in Fig. 8. An object with a columnar arrangement of conductive materials similar to that in [15], it is capable of three-dimensional input. For the hemispherical object shown in Fig. 8 (a), when a user touches on the upper surface of the object, not only the two-dimensional location but also the object's height can be estimated. For the topographical object shown in Fig. 8 (c), when a user touches on the object, depending on the height of the touching location, the application identifies the parts of the object.

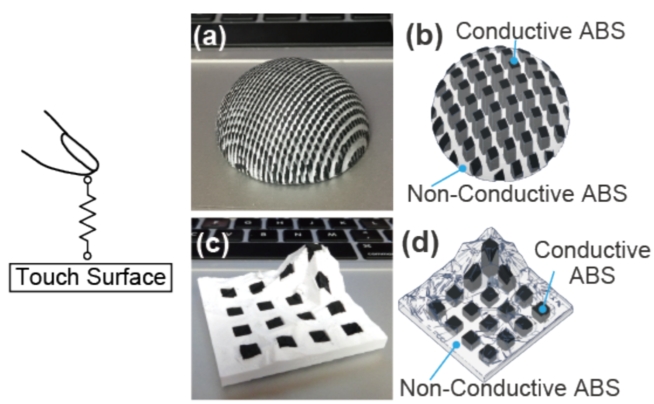

Figure 8. (a) Hemispherical object with a columnar arrangement of conductive materials; (b) Internal structure of (a); (c) Curved surface object with a columnar arrangement of conductive materials; (d) Internal structure of (c).

There is a common method for detecting the position and rotation of a tangible object by using an asymmetric multitouch pattern [26, 6, 17] with conductive materials. Figure 9 shows an Ohmic-Touch extension of this method. The black conductive portion at the bottom is extended to the top plane and they are then connected to each other. When the user

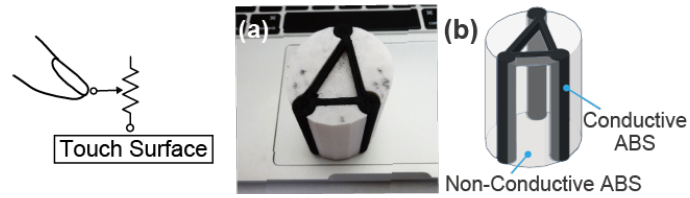

Figure 9. (a) Tangible object with 3 touch points; (b)Internal structure of the object.

touches the conductive portion that appears on the side, the application detects not only the position and rotation of a tangible object but also the position of the conductive area where the user touched.

Functional Touch Pens and a Dial

Figure 10 shows touch pens having a fixed resistor of various resistance values. In Fig. 11 (a), has a potentiometer, (b) has a built-in pressure sensor, and (c) has a tangible dial with a variable resistor built in. We implemented a drawing application for these touch pens. In Fig. 10, because each touch pen has different fixed resistors, the pens can be identified. This allows the user to draw in the color corresponding to each pen. By rotating the knob of the potentiometer in Fig. 11(a) thereby changing the resistance value, the user can zoom in or out while using a drawing tool in an application. In Fig. 11(b), the resistance of the pressure sensor varies depending on the grip force on the pen. This allows the user to change the line width as desired. In Fig. 11(c), the brightness can be changed by rotating the dial of the variable resistor mounted on the object. In our feasibility study, the differences in the value of leakage current among participants are small (<5%). Thus, the touch pens shown in Fig. 10 and Fig. 11(a) can also be used to identify multiple users. That is, by allocating users to each resistance value, each user can be identified by the pen they are using.

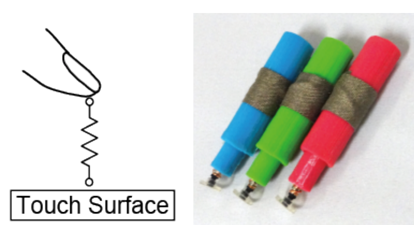

Figure 10. Color Pens with fixed resistors (10 kΩ, 50 kΩ, 100 kΩ).

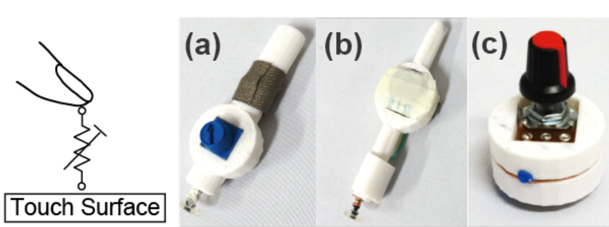

Figure 11. (a) Touch pen with a potentiometer (0 kΩ–100 kΩ); (b) Gripping pen with a force sensor FSR402 (10 kΩ–10 MΩ); (c) Dial object with a variable resistor (0 kΩ–100 kΩ).

Deformable Soft Toys

Figures 12(a) and (b) are soft toy objects fabricated with a flexible sensor and a force sensor. By bending the doll in Fig. 12(a) such that it bows, the resistance value of the flexible sensor changes. By pressing the doll in Fig. 12(b), the resistance value of the force sensor changes. Depending on the deformation operations, corresponding interactions can be determined. This is the realization of Flexibles [26] using the approach proposed in this paper, i.e., using the change in the resistance component of the impedance.

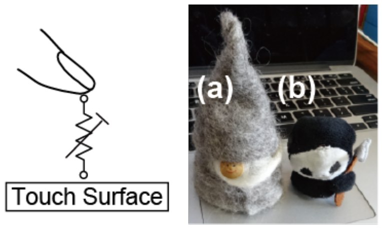

Figure 12. Soft toys (a) with a flex sensor (25 kΩ–60 kΩ) and (b) with a force sensor FSR402 (10 kΩ–10 MΩ).

Sensing Objects

Figures 13(a) and 13(b) show tangible objects that use the passive untouched capacitive widgets (PUCs) [28] principle. PUCs are objects with two or more touch points that are electrically connected. When a PUC is placed on a capacitive touch surface and when one touch point is scanned, the other touch point acts as a ground and maintains the equivalent state of the human touch. By using this, we prototyped objects that have a passive variable resistance sensor connected between the two touch points. The interaction corresponding to the resistance value of the sensor is provided.

Figure 13(a) is a cup object with a temperature sensor (thermistor) on the bottom. When liquid is poured into the cup, the resistance value of the thermistor changes. From this, the presence of the liquid as well as its temperature can be sensed on the touch surface. Therefore, it can provide a function similar to that of MediaCup [4]. Figure 13(b) is an object with a light sensor (CdS cell). The touch surface is able to sense the ambient brightness by simply having it placed on it. Because the objects in Figs. 13(a) and 13(b) only require objects to be placed on the touch surface, they can be used for educational purposes, such as for the understanding of the functions of electronic components and sensors, or in the training of sensor-based programming.

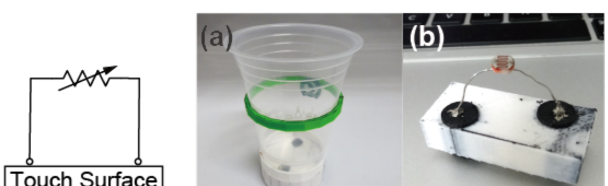

Figure 13. Tangible objects (a) with a thermistor (0.8 kΩ–330 kΩ) and (b) with a CdS cell (10 kΩ–1 MΩ).

DISCUSSION

In this study, we investigated the feasibility of the proposed touch interaction method with a specific laptop computer. Depending on the devices, the grid spacing of the electrodes or the detectable range of resistance value is estimated to be different. Although calibration is required for each touch device model for these reasons, it is considered that the proposed technique is widely adaptable in commercial touch surface devices. We developed our prototype on a macOS development environment where the API and framework to acquire raw data leakage current is available. In the iOS and Android environments, a similar API is not commonly accessible. However, it is known that capturing raw values in correlation with leakage current data is possible by using an Android's debugging interface [26, 10, 8, 18, 30]. Considering that both capacitance and resistance affect impedance, the proposed method is also applicable to Android devices, including smartphones and tablet PCs. Ohmic-Touch interactions with an underlying integrated display will be possible using these devices.

We are currently considering the following possible applications of Ohmic-Touch for smartphones.

1. Integrating a force-sensitive resistor into a smartphone or tablet PCs case, to provide additional gripping operations.
2. Attaching touch area extensions to an HMD adapter like Google Cardboard to facilitate richer operations.

In the feasibility study for a laptop computer, the ground condition was controlled (sitting on the chair, without shoes on, and using the AC adapter). In our unofficial experiment, the user's posture (i.e., sitting/standing), with or without shoes on, resulted in a maximum fluctuation of 5% of the value of the leakage current. The condition of using the AC adapter or using the internal battery resulted in a maximum fluctuation of 7% of the value of the leakage current. This effect is estimated to be more pronounced when using mobile devices because of their utility in more diverse situations, as compared to using laptop computers. However, it is expected to improve by correcting the value of leakage current from the method for estimating grasping (i.e., one/two-handed) [5, 22] or usage state.

When touching an object of an intervening conductor, we observed that the leakage current is affected by the size of the contact area between the object and the finger. In the feasibility study, the error was small because the touch point was a thin wire. However, for some objects shown in the previous section, it may be necessary to redesign the size of the finger-touch area small enough to ensure a stable detection.

CONCLUSION

In this paper, we proposed a method called Ohmic-Touch that extends the modality of touch inputs using the electric resistance on commercial capacitive touch surfaces. Ohmic-Touch provides a series of interactions without requiring the touch object to be powered. As such, the proposed method allows for the use of inexpensive materials. Therefore, the proposed can be a practical technique for providing greater modality to inputs on touch surfaces. We believe this paper will contribute to advances in the HCI community as a basis for expanding input modalities for capacitive touch surfaces. In a future study, we will implement effective applications that utilize the features of this technique for mobile devices and its efficiency will be evaluated.

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