

Ohmic-Sticker: Force-to-Motion Type Input Device that Extends Capacitive Touch Surface

Kaori Ikematsu^{1,2}, Masaaki Fukumoto², Itiro Siio¹

¹Ochanomizu University ²Microsoft Research
Tokyo, Japan Beijing, China

k-ikematsu@acm.org fukumoto@microsoft.com siio@acm.org

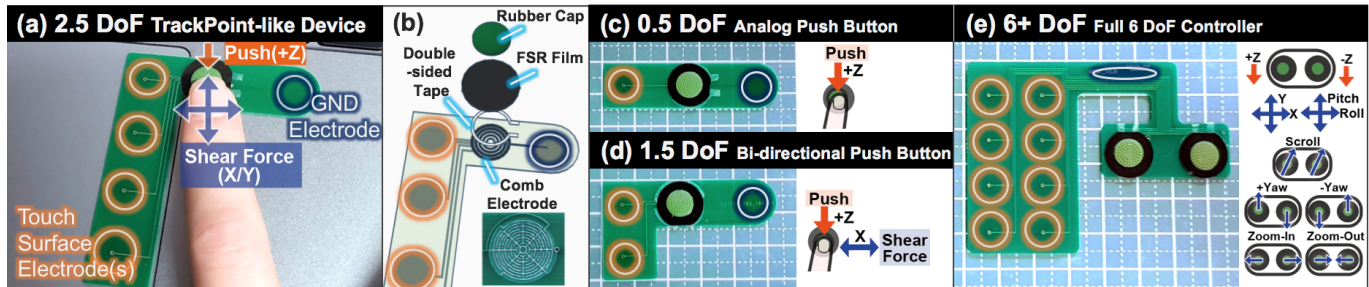


Figure 1. Overview of Ohmic-Sticker: (a) it works simply by attaching to a commercial touch surface; (b) the simple FSR-based structure enables thin (less than 2 mm) form factors; (c–e) 0.5 – 6 DoF or more force-sensitive inputs can be realized.

ABSTRACT

We propose “Ohmic-Sticker,” a novel force-to-motion-type input device to extend capacitive touch surfaces. It realizes various types of force-sensitive inputs by simply attaching on to commercial touchpads or touchscreens (touch surfaces). A simple force-sensitive-resistor-based structure enables thin (less than 2 mm) form factors and battery-less operation. The applied force vector is detected as the leakage current from the corresponding touch surface electrodes by using the Ohmic-Touch [17] technology. Ohmic-Sticker can be used for adding force-sensitive interactions to touch surfaces, such as analog push buttons, TrackPoint-like devices, and full 6 DoF controllers for navigating virtual spaces. In this paper, we report a series of investigations on the design requirements of Ohmic-Sticker and some prototypes. We also evaluate the performance of Ohmic-Sticker as a pointing device.

Author Keywords

Force-to-Motion; Capacitive Touch Surface; Trackpoint.

CCS Concepts

•Human-centered computing → Pointing devices;

INTRODUCTION

Touch-type pointing devices that provide motion-to-motion inputs (e.g., trackpad) can be seen on most modern laptop PCs and 2-in-1s; however, it is difficult to find stick-type pointing

devices that provide force-to-motion¹ inputs (e.g., TrackPoint [26]). The possible reasons for the decline of TrackPoint are thickness of the sensor (the typical sensing mechanism requires 3 – 5mm thick), pointing performance (performances in force-to-motion inputs are slightly inferior than that in motion-to-motion inputs) [2, 22]) or manufacturing cost. However, its small footprint allows it to attach onto various places, especially for portable and mobile devices having small surfaces. In addition, force-to-motion pointing does not require large finger or hand movements from user’s convenient position. There are no clutching actions (repositioning) needed for continuous inputs, e.g., scrolling, dragging or long-distance cursor movements [29, 3]. These are the reasons for several TrackPoint lovers still existing, even though PC makers hesitate to adopt TrackPoint-like devices. Therefore, it would be a promising DIY add-on option if a force-to-motion type pointing device can be easily attached to the existing touch surfaces while retaining their thin form factors and conventional touch interactions. Considering its advantages, the non-TrackPoint lovers will also be benefitted.

In this paper, we propose “Ohmic-Sticker”, a novel force-to-motion input device that provides 0.5 – 6.0 degrees of freedom (DoF) or more operations. As shown in Fig. 1 (a–e), it realizes various force-sensitive interactions simply by attaching onto touch surfaces. The force-sensitive-resistor (FSR)-based structure enables battery-less operation and thin (less than 2 mm) form factors. The force vector applied on the structure can be detected as a shunting current from the corresponding touch surface electrodes using Ohmic-Touch [17] technology. The main advantages of Ohmic-Sticker are as follows: (1) low-cost battery-less attachment for touch

¹Force-to-motion input is a method of ratio control force to move a particular component, e.g., cursor movement or scrolling operation.

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surface (~\$2), (2) both Ohmic-Sticker and the existing touch surface can be used simultaneously, (3) the simple FSR-based structure realizes various force-sensitive interactions, e.g., analog push actions, TrackPoint-like operations, and full 6DoF controller operations, (4) compatible with not only the integrated trackpad in a laptop but also a smartphone and a tabletop-type touch surface. Therefore, back-of-device interactions for a smartphone and a controller for a large-sized touch surface can be realized. We conducted investigations on the design requirements of Ohmic-Sticker. Based on the result, we implemented prototypes of Ohmic-Sticker, and focusing on the realization of a TrackPoint-like device, we conducted an experiment to evaluate its basic performance. Finally, we reported applications and use cases for Ohmic-Sticker.

RELATED WORK

This study concerns the areas of force-to-motion type inputs and extending interaction on touch surfaces. Rutledge et al. [26] proposed an early form of an isometric joystick in 1990. Thereafter, it became popular because IBM commercially introduced this joystick as TrackPoint in 1992 on their laptop PC (ThinkPad 700C). TrackPoint senses the applied force and its direction using resistive strain gauges. Other pointing sticks include capacitive pointing sticks [27], which have a conductive spring and capacitive force sensor at the bottom of the stick. In a surface-mount pointing device [31], several sensors are mounted on the base of the device; it senses the amount of strain, which created at the base, in response to the applied force. Because of the vertical space required to mount the stick, it is difficult to reduce the thickness when these structures are used. Stick-type pointing devices have also been used for interaction in mobile devices [35, 37].

An emerging stream of research investigates the manner in which interaction on capacitive touch surfaces can be enhanced. To provide continuous inputs for touch surfaces, some tangible interaction techniques using shunting current from a touch surface's electrode have been proposed. Shunting current changes according to the impedance of the path from the touch surface to the GND. Based on this principle, Flexibles [28] utilizes the change in the capacitance component of impedance, and Ohmic-Touch [17] utilizes the change in the resistance component of impedance. Because a capacitive sensor is made of 3D printed conductive material, [28] requires a bigger or thicker structure to realize sufficient change in capacitance. Similar to Ohmic-Touch [17], Ohmic-Sticker utilizes the change in the resistance component to realize a continuous input. However, in contrast to [17, 28], which use a human body as the GND, Ohmic-Sticker utilizes a touch surface device (casing) as the GND to increase stability by reducing the noise from shunting current. For example, finger dryness, size, and angle (i.e., pitch and yaw), AC or battery condition, a path to the GND, etc. actually affect the shunting current measurement. Using additional hardware, these differences can be negated.

In other interaction techniques, shunting current is mainly utilized for measuring the capacitance component of impedance [14, 11]. Various interaction techniques use grid images of shunting current (generally called “capacitive raw

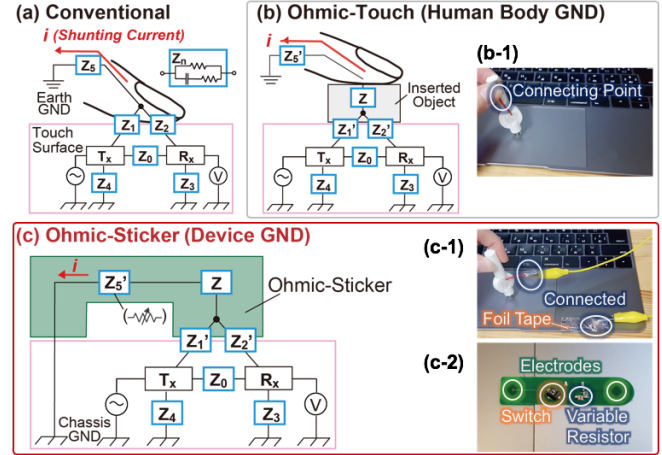


Figure 2. (a–c) Equivalent circuits of conventional touch and GND connection methods; (b-1), (c-1) and (c-2) Experimental apparatus.

images”²) have been proposed: for example, recognizing user’s body part features for biometric authentication [14, 11], detecting a finger’s proximity [13], differentiating between the touches of fingers and palm [19], identifying individual fingers [21], estimating finger’s pitch and yaw [36], or the contact size and shape [25] on a touch surface.

Researchers have shown that a touch surface can identify tangible objects, and recognize the x-y location and rotation angle of an object [39, 38, 9]. More recently, researchers have developed attachments [40, 32, 18] or objects [12, 4, 23] using conductive materials that can extend the touch areas to the outside of a touch surface, to provide simple on/off touch inputs from conductive buttons mounted on the object [40] or to provide touch gestures from the surface of the object such that the touch location on the surface changes accordingly [4, 12, 18]. Unlike previous motion-to-motion approaches, Ohmic-Sticker provides force-to-motion inputs.

TOUCH DETECTION PRINCIPLE

A capacitive touch surface has a structure in which the transmission electrode (T_x) and the receiving electrode (R_x) groups are orthogonal to each other. Figure 2 (a) shows the equivalent circuit at the intersection of a pair of electrodes. When the T_x is excited by a high-frequency signal, the R_x receives this signal through the impedance network. When a conductive and grounded object approaches the intersection, a part of the signal from T_x shunts to the GND (i), and the signal received by R_x is attenuated. The touch surface determines the touching or non-touching states depending on the amount of shunting current, which is shunted to the GND by the touch. This current depends on the impedance of the path to the touch. As shown in Fig.2 (b), the change in impedance is utilized for continuous input on the touch surface.

Ohmic-Sticker utilizes the above-mentioned principle. As shown in Fig.1 (b), it has a simple FSR-based structure that changes its resistance according to the applied force. When the structure is placed in the path extending from the touch point to GND, the amount of shunting current changes based

² Capacitive raw images are typically not exposed to the application layer; therefore, to access this, kernel modification is required.

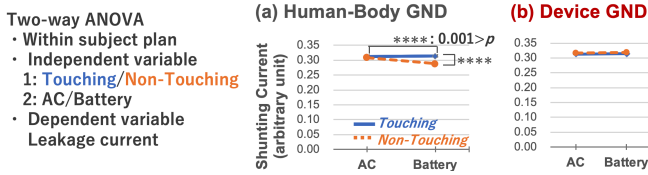


Figure 3. Mean shunting current for each GND connection method.

on the applied force. By detecting the applied force vector, Ohmic-Sticker realizes various force-sensitive inputs on the touch surface.

INVESTIGATIONS ON DESIGN REQUIREMENTS

We investigated the design requirements of Ohmic-Sticker. First, to implement Ohmic-Sticker, there are two options for connecting the GND, as follows:

- via the human body (Human body GND, Fig. 2 (b))
- via the device casing (Device GND, Fig. 2 (c))

Generally, circuit boards inside a touch surface are electrically connected to the device casing. As shown in Fig. 2 (c), device GND is the method of connecting one end of the conductive part of Ohmic-Sticker onto the touch surface and the other end to the casing of the touch surface. Both the GND methods have advantages and disadvantages. First, in the human body GND method, the GND condition of the user or individual differences in body impedance may result in shunting current fluctuations. This effect will not occur in the case of a device GND. However, as Voelker et al. [34, 33] reported, most modern touch surfaces have adaptive filtering functions for long-time stationary touch inputs. The purpose of adaptive filtering is to discriminate stationary inputs from fingers or touch pens. Such unintentional signals are often caused by overlying objects or outgoing electrical noise. This causes the touches by a stationary object (such as PUCs [34]) to disappear after a short while. In the human body GND, the effect of filtering is assumed to be relatively small because the current leaks and changes during user's operations. However, in the device GND, a constant amount of current leakages occurs while the device is attached, and the calibration effect should also be considered. Given the potential issues, we conducted the following investigations to choose the most suitable GND connection method³.

Effect of GND Conditions

We investigated effect of the GND connection described in Fig. 2 on the stability of shunting current measurement. In this experiment, we selected the following GND conditions. (1) Touching or non-touching between a user's body and casing, (2) Connecting the touch surface to an AC adapter or using a battery. Regarding (1), when a user uses a laptop PC, the condition changes frequently (e.g., putting/leaving hands on the palm rests or putting a laptop PC on a lap or a table). Regarding (2), shunting current is stable when the laptop is connected to the GND through the AC adapter. However, it

³ Notably, the consideration will not always be necessary if types of hacking such as kernel modification are executed. However, to run Ohmic-Sticker on off-the-shelf (unmodified) touch surfaces, we conducted the investigations.

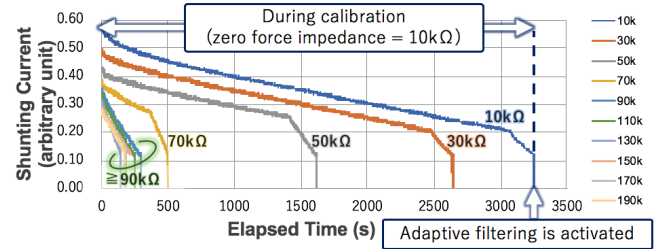


Figure 4. Temporal changes in the value from the API (in correlation with shunting current) for each resistance value.

is unstable in battery-powered devices, which often rely on a weakly coupled GND reference [10].

Six participants (four females and two males, aged 23–57) were invited to participate in the experiment. The participants touched the surface with a touch pen that could switch between the human-body GND (Fig. 2 (b-1)) and device GND (Fig. 2 (c-1)). The touch operation was performed at the center of the touch surface with four types of combined GND conditions (i.e., (1) and (2) conditions) and two types of GND connection (i.e., human-body GND and device GND) methods. We used a MacBook (Apple, Early 2016, macOS 10.13). The size property value of the third-party library for MultitouchSupport.framework⁴ provided the data correlation with shunting current (see details in [17]). We recorded 5 sec of shunting current with 120 Hz sampling rate.

Result. The mean shunting current for each GND condition and connection is shown in Fig. 3. In the device GND, shunting current was stable in all the GND conditions (the mean fluctuation was less than 1.0 %). In the human body GND, shunting current was stable in the AC adapter condition. However, in the battery condition, the touching condition tended to increase the shunting current compared to the non-touching condition (the mean fluctuation was less than 9.0 %). We confirmed that the device GND is more stable than the human body GND; therefore, we selected the former.

Suppression of Adaptive Filtering

The force sensor used in Ohmic-Sticker maintains a certain resistance value without the application of any pressure force. Shortly after attaching it on a touch surface, because of the path via the force sensor or the weak AC coupling between the electrode on the top layer of the PCB and the GND, a shunting current is detected when there is no pressure force on the force sensor. After a certain time elapses, the touch input ceases to be detected because of the adaptive filtering of the touch surface. It is considered that the effect of filtering changes depending on the impedance value without applying any force (hereinafter called zero-force impedance). Therefore, in the case of a device GND, the zero-force impedance value should be set considering the characteristics of the filtering.

We used the same touch surface as in the above-mentioned investigation by connecting it to the AC adapter. We prepared an experimental apparatus (see Fig. 2 (c-2)) with a switch and variable resistors connected to the touch surface electrode and GND electrode. It was attached to the touch surface using a double-sided Z-axis conductive tape (9703, M3) with the

⁴ http://hci.rwth-aachen.de/guide_trackpad

switch turned off. Next, we turned on the switch and thereafter a shunting current began to be detected. When the current was detected, the value was logged at a sampling rate of 30 Hz. After the activation of filtering (at the time shunting current ceased to be detected), we decreased the resistance value of the apparatus to 0 k Ω to check if the shunting current was detectable again. The above-mentioned procedure was repeated for ten impedance conditions, which were set by adjusting the resistance value of the variable resistor (10 – 190 k Ω , with 20k Ω interval).

Result. Figure 4 shows the results of the change in shunting current. In either condition, the measured shunting current decreased with time, and finally ceased to be detected. Note that, the actual resistance value of the apparatus was not changed while executing the calibration, and therefore, the decrease in current indicates the effect of calibration. Regarding the operation of the apparatus with decreased resistance value after the filtering, shunting current was detectable again for resistance values in the range $>30\text{k}\Omega$, but was not detectable for $\leq 30\text{k}\Omega$. The shunting current increased when the resistance value of the apparatus was decreased, thereby negating the adaptive filtering. However, in the case of resistances lower than 30 k Ω , the amount of background shunting current was already too high, and the filtering was not negated. Therefore, except when the zero-force impedance is exceedingly low ($\leq 30\text{k}\Omega$), the shunting current is detectable even after the filtering is activated, if the impedance of the apparatus is decreased compared to the zero-force impedance.

OHMIC-STICKER

Based on the investigations, the design requirements for Ohmic-Sticker are determined as follows.

- Using the device GND method.
- Setting a zero-force impedance value that is detectable after the filtering of a touch surface.

Figure 1 (b) shows the basic structure of Ohmic-Sticker. The sensor structure was designed with reference to MicroNav 360 [7]. Ohmic-Sticker consists of a rubber cap (1.0mm thick, $\varnothing 8.0\text{mm}$), an FSR film (0.12mm thick, $\varnothing 14.0\text{mm}$, plastic film with carbon powder applied to one side), circular double-sided tape (0.16mm thick, $\varnothing 14\text{mm}$, with a small gap for a pressure vent), and a two-layered printed circuit board (PCB, 0.6mm thick). The FSR film is attached on a comb electrode installed on the PCB using a double-sided tape. The rubber cap is attached on the film with an adhesive. One end of the comb electrode is connected to an electrode to be placed on a touch surface (touch surface electrode), and the opposite end is connected to an electrode to be placed on the device casing (GND electrode).

The conductive side of the film faces the comb electrode. The circular double-sided tape acts as a spacer. When an external force is applied to the film, the contact area between the film and the comb electrode is changed resulting in a change in the resistance value, and therefore, it functions as a force sensor. The more the electrode area is in contact with the film, the lower is the resistance. A touch surface detects the change in the resistance value of the force sensor as a change in shunting current. Therefore, Ohmic-Sticker operates by simply

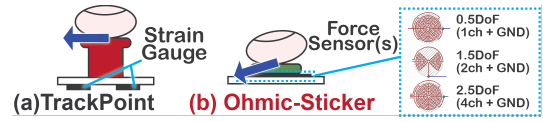


Figure 5. Differences in operation for each device.

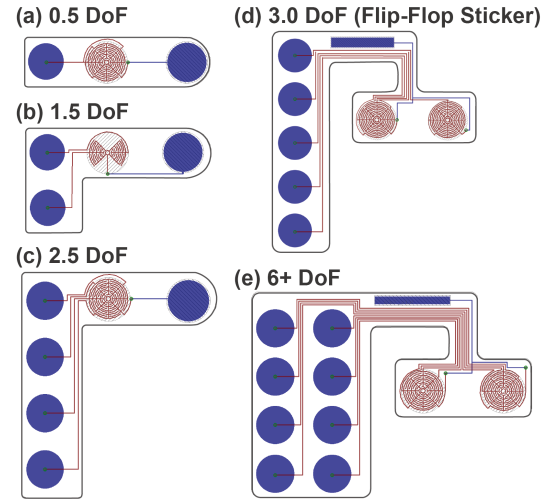


Figure 6. Electrode and wiring patterns for each DoF.

attaching onto a touch surface. Owing to the differences in the sensor structure, the operation of Ohmic-Sticker differs slightly from that of TrackPoint. That is, both devices can be operated by applying shear force; however, for Ohmic-Sticker, the vertical component of the applied force vector should have a greater magnitude compared to that for TrackPoint (Fig. 5).

Layout Patterns of the Electrodes

Figure 6 shows the electrode patterns of Ohmic-Stickers that realize 0.5–6+ DoF operations (Figure 6 (d) is described in the later section). Here, we describe each pattern and corresponding operations. All patterns of prototypes have sufficiently high zero-force impedance for redetection after the adaptive filtering.

0.5 DoF Pattern has one touch surface electrode connected to a GND electrode via a comb electrode. When an external force is applied to the force sensor, a touch surface detects the change in the resistance value. It provides simple one-directional (0.5 DoF) pressing operations.

1.5 DoF Pattern has two touch surface electrodes connected to a GND electrode via a two-divided comb electrode. When a shear force is applied to the right or left side of the force sensor, the touch surface detects the change in resistance value of one part of the sensor. It provides bi-directional (1.0 DoF) pressing operations. In addition, when applying vertical pressure force on the sensor, the resistance value in both parts of the force sensor change simultaneously. This enables 0.5 DoF pressing.

2.5 DoF Pattern has four touch surface electrodes connected to a GND electrode via a four-divided comb electrode. When a shear force is applied to the force sensor, the touch surface detects the change in the resistance value of one part of the sensor. In the case of applying a shear force obliquely, the resistance values of the two adjacent parts of the force sensor

are changed. It provides two-dimensional (2.0 DoF) operations and realizes TrackPoint-like operations.

6+ DoF Pattern has eight touch surface electrodes connected to a GND electrode via two four-divided comb electrodes. The left/right column of the touch surface electrodes is connected to the four-divided comb electrode installed on the right/left side. The operation of the left force sensor is the same as that of the 2.5 DoF pattern operations. The operation of the right force sensor is similar to that of the left force sensor; shear force is applied in every direction for pitch/roll operations, and the pressure force is applied for -Z operation. In addition, a shear force is applied in the opposite direction on both the sensors for yaw operation. Zooming or scroll operation can also be added.

CHARACTERISTICS AND SPECIFICATION

To implement a software that provides TrackPoint-like force-to-motion operations, we investigated the mapping between (1) the force and shunting current of Ohmic-Sticker and (2) the force and cursor speed of the TrackPoint. Based on the investigations, we derived the mapping function between the force and cursor speed for Ohmic-Sticker.

For investigation (1), we used the Ohmic-Sticker having one direction of 2.5DoF pattern attached to the touch surface of the MacBook (Apple, Early 2016, macOS 10.13) with the AC adapter connected. We performed each press onto the Ohmic-Sticker using a digital force gauge (IMADA, ZTS-50N). We logged the shunting current and applied force, simultaneously. As shown in Fig. 7 (a), Ohmic-Sticker can sense continuous intensities of applied force (from 0.6 to 2.5[N]). At approximately 2.5 [N] or more, the measured shunting current tended to become saturated.

For investigation (2), we used a ThinkPad Bluetooth keyboard with TrackPoint (Lenovo, 0B47208, driver version 1.5.6.0) and Vaio Ultrabook SVT (SONY, 13139CJS, Windows8). We set the cursor speed at the default level in the driver. We used the digital force gauge similar to that in the above-mentioned task. To exclude the effect of dynamic acceleration [1], the cursor speed was measured for a total of 7 sec, of which the data for the first 2 sec were excluded. The cursor speed was measured as px/s on the display (Iiyama, ProLite B2712HDS, 1920 × 1080 px). Figure 8 (orange line) shows the results of the applied force and the measured cursor speed.

As shown in Fig. 8 (dotted line), we implemented the force-speed function for Ohmic-Sticker by referring to the

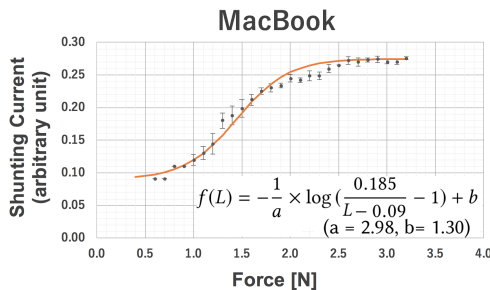


Figure 7. Mean shunting current (with standard deviations) for press input. The mapping function is shown in orange.

transfer function of TrackPoint. Owing to the differences in the detectable force range between TrackPoint (approximately 0.4 – 3.0 [N]) and Ohmic-Sticker (approximately 0.6 – 2.5 [N]), we modified the transfer function as follows. For the range $F \leq 2.5$ [N], the modified function used the same slope of the curve as the original function, except for moving parallel to the x-axis direction by +0.20 (differences in the required force to detect the input). For the range $F > 2.5$ [N], the changes in the shunting current are indistinguishable, therefore; we use a constant value for this range.

EVALUATION

To evaluate the performance of Ohmic-Sticker, we conducted an experiment involving a traditional pointing task. We compared Ohmic-Sticker to a baseline performance i.e., TrackPoint. This experiment was conducted in conformance with Fitt's law [8]. We used Fitts' Task Two [30, 24], a software that provides a multi-directional point-and-select task. As shown in Fig.9, eleven circles and a cursor were displayed on the screen. For each trial, the target to be selected was highlighted in red, and once the target was selected, the target in the opposite location was highlighted. The participants controlled the cursor by using TrackPoint or Ohmic-Sticker with an index finger. The distance A between two sequential targets was 256 or 512 px. The target diameter W was 36 or 48 px. One session consisted of a random order of the four conditions and the device condition was counterbalanced. The participants performed three sessions as a practice trial, and then two sessions for actual trials, for each device. We calculated the following indexes (see also Fig. 9).

- **Movement time (MT):** the mean time for each trial (clicking 11 targets).
- **Error Rate (ER):** the percentage of targets selected while the cursor is located outside the target.
- **Throughput (TP):** in bits per second, a composite measure based on both the speed and accuracy of performance proposed by Fitts [8].

For the TrackPoint tasks, we used a ThinkPad Bluetooth keyboard with TrackPoint connected to a Vaio Ultrabook. For the Ohmic-Sticker tasks, we used Ohmic-Sticker with the above-mentioned transfer function. The screens of the PCs were blacked out and the PCs were connected to the display (ProLite B2712HDS, Iiyama, 1920 × 1080 px).

Ten participants (eight females and two males, aged 21 to 57, all right-handed, three had experience operating TrackPoint) were invited to participate in the experiment. The participants

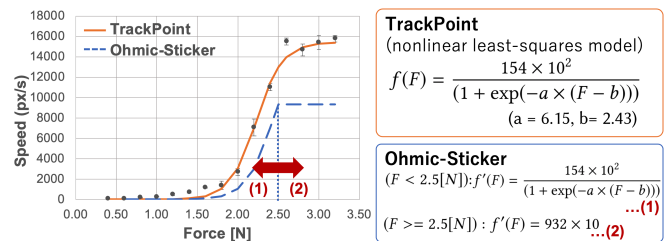


Figure 8. Orange: mean cursor speed (with standard deviations) and the mapping function of TrackPoint; Blue (dotted line): the mapping function for Ohmic-Sticker.

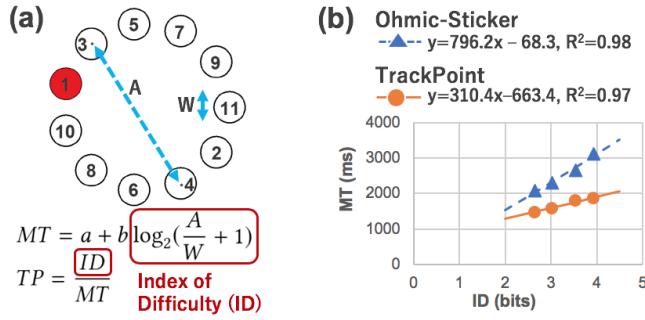


Figure 9. (a) Parameter settings for Fitt's law Task. The constants a and b are empirically determined; (b) Fitts' law fitness for Ohmic-Sticker and TrackPoint.

selected the targets by pressing the left button equipped on the keyboard while using TrackPoint, and pressing the left corner of the touch surface while using Ohmic-Sticker with their nondominant hand. In total, we recorded the data for 11 targets \times 4 parameters \times 2 sessions \times 2 device conditions \times 10 participants = 1760 trials.

Result. Figure 9 shows the result of the performance for each device. In the 1408 trials, 36 error attempts occurred. Both device conditions exhibited good fits to Fitts' law, with $R^2 > 0.97$. TP resulted in 1.4 (bps) for Ohmic-Sticker and 1.8 (bps) for TrackPoint. The mean throughput of Ohmic-Sticker was 79 % of TrackPoint. ER resulted in 1.4 % for Ohmic-Sticker and 4.1 % for TrackPoint. The ER for Ohmic-Sticker was lower than those for common Fitts' tasks (e.g., 3–5 %, [6]). The data were analyzed using a two-way ANOVA (within subject plan, independent variable (1) Ohmic-Sticker or TrackPoint condition, independent variable (2) sessions 1 or 2 condition, dependent variable: TP and ER , respectively) for each dependent variable. The main effects of the independent variables were analyzed and the results showed that there were significant differences in the device condition [$F(1, 9) = 17.83, p < .005$] (TP), [$F(1, 9) = 15.04, p < .005$] (MT) and [$F(1, 9) = 6.79, p < .05$] (ER). No significant trial condition effect and interaction effect were observed in any of the analyses.

DISCUSSION AND LIMITATIONS

Validity of the Force-Speed Function. One possible reason for the lower throughput in Ohmic-Sticker is the force-speed function. Our implementation of the function was based on the reverse engineering of TrackPoint. However, the actual implementation of TrackPoint includes at least the dynamic pointing function [1]. Our implementation does not fully imitate TrackPoint. Thus, there is room for improvement.

Mounting Position. After the evaluation, three participants (who had prior experience with TrackPoint) commented that similar to TrackPoint, if Ohmic-Sticker enables a user's hands to remain close to the keyboard home position, it will be more attractive. Typically, TrackPoint is embedded between the G, H, and B keys on the keyboard. It is difficult to attach Ohmic-Sticker at that position. However, as shown in Fig. 10 (a), it is possible to attach Ohmic-Sticker below the space key. In this case, to prevent direct coupling between the finger and the touch surface under the Ohmic-Sticker, the PCB should

be thick (at least 1.0mm thick). In a case using a clamshell laptop PC, although the thickness of the Ohmic-Sticker is less than 2.0mm, it is considered to interfere with the screen when closing it. Attaching a cushioning with the same thickness as that of Ohmic-Sticker can prevent such interference.

Interference with the Existing Device Form Factors.

Ohmic-Sticker occupies a part of the touch surface, i.e., a space including a 10-mm-diameter touch surface electrode(s). In the case of using 2.5 DoF on a 12-inch MacBook, 16% of the input area will be occupied; thus, 84% of the remaining area is still available for conventional inputs. Regarding potential false activation, in the case in which a user accidentally touches the touch electrodes or lines connecting the touch surface electrodes and the comb electrode on Ohmic-Sticker, the shunting current will rise much faster than the pressing of the pointing head, and hence, utilizing the differences in the rising speeds, unintended activation can be avoided.

Advantages as Add-on option. After the evaluation, eight participants commented that they preferred the trackpad over Trackpoint or Ohmic-Sticker for general pointing operations; however, they felt that force-to-motion inputs are suitable for long distance cursor movements or continuous inputs. They also commented that since the existing trackpad can be used simultaneously, Ohmic-Sticker is an attractive extension for the trackpad. Specifically, operations such as performing shorter cursor movements by the trackpad and longer movements by Ohmic-Sticker are preferable.

Adaptability of the Investigation Results. In this study, we focused on the realization of a TrackPoint-like input device; thus, the technical and user evaluations were mainly performed for it. However, considering that the same comb electrode (i.e., 1/4 fan-shaped) as 2.5 DoF is also used in 1.5 DoF and 6+ DoF, the characteristics of the force-to-shunting current mapping are the same. Regarding the 0.5 DoF having a round-shaped comb electrode, owing to the lower zero-force impedance than other DoFs, the mapping is not exactly the same as that for the 2.5 DoF. However, the other parts (i.e., the thickness of a PCB, density of the comb electrode, film, and cap) are the same as that for 2.5 DoF; thus, the mapping is close to it. The results of investigations on design requirements are common for all DoFs of Ohmic-Stickers.

In the this study, we used a built-in touch surface with a casing made from metal. In the case of using a touch surface with a plastic casing, considering that the inside of the casing is shielded and grounded to reduce electromagnetic wave interference, the device GND method could feasibly be adapted by using a bigger GND electrode.

APPLICATIONS AND VARIATION

In this section and the video figure, we present a number of applications and variation of Ohmic-Sticker.

Intuitive Z-axis Operations. One concern for 6+ DoF Ohmic-Sticker is assigning both +Z and -Z operations to a pressing movement towards the same direction. The Z-axis operations are not orthogonal compared with X/Y-axis operations, thus not very intuitive. This can be improved by introducing the Flip-Flop Sticker [15] mechanism described



Figure 10. Variations of Ohmic-Sticker use cases.

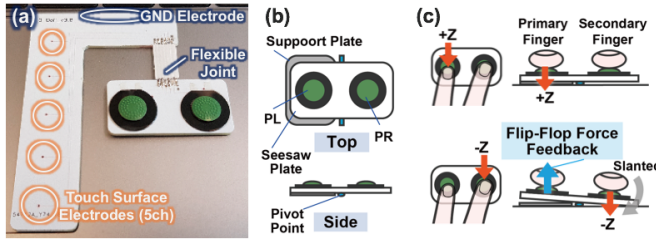


Figure 11. (a) The structure of 3.0 DoF Flip-Flop Sticker; (b) A loosely creased PET film is used for the pivot point; (c) The seesaw-like mechanism enabling flip-flop force feedback.

in Fig. 11. Basically, Flip-Flop Sticker has the same device structure as Ohmic-Sticker (Fig. 6 (d)). However, it has a pivot point that is attached to the bottom of the device (see Fig. 11 (b)). The pivot point realizes a seesaw-like mechanism that switches up and down movement around it. As shown in Fig. 11 (c), when a pressure force is applied to the +Z pointing head, a support plate retains the seesaw plate horizontally. However, when the pressure force is applied to the -Z pointing head, the seesaw plate slants around the pivot point. The small seesaw movements generate flip-flop (upward) movements toward the operation finger and provide the user with a mental image of a stepping-up motion. Generally speaking, any kind of raising actions against gravity may cause fatigue. Our proposed structure provides upward motion without manually raising a finger. In addition, the Z-axis motions (+Z and -Z) are orthogonal. Therefore, our proposed structure realizes both low fatigue and intuitive Z-axis operations. The flip-flop feedback is considered to be effective especially for eyes-free use cases e.g., adapter for a cardboard HMD (Fig. 10 (b)).

Dual Functions. As discussed above, though Ohmic-Sticker occupies part of the touch surface, Ohmic-Sticker and the existing touch surface can be used simultaneously. It is possible to assign different functions for each pointing device (see Fig. 10 (c)). For example, assigning different coordinates for the cursor movement: relative pointing for Ohmic-Sticker,

absolute pointing for a touch surface; different control-display (CD) ratio for each device: quick long-distance cursor movement with higher CD ratio for Ohmic-Sticker, precise and tiny cursor movement with lower CD ratio for a touch surface, or a multi-handed interface can be provided. In addition, assigning touch gestures (e.g., scrolling, swiping or pinching) to the Ohmic-Sticker operations is also possible.

Back-of-Device Interactions. Single-handed operations of a smartphone lead to an unstable grip due to the finger's limited reachability. One of the promising approaches is back-of-device (BoD) interaction such as [20, 5]; however, [20, 5] require additional active sensors or an additional touch panel on the back side. Ohmic-Sticker is one solution for the issue. As shown in Fig. 10 (d), connecting the force sensor part of Ohmic-Sticker to the touch surface electrode part by using the flexible joint. While the electrodes partially hide the screen, BoD interaction can be provided without battery. It is possible to assign zooming-in/out or rotating operations that are typically performed by multi-touch. For the implementation, we used Nexus 5 (having a modified kernel implemented by Le et al. [19]) that provides the capacitive raw images.

Dual Joysticks. Figure 10 (e) represents a dual-stick controller. Two Ohmic-Stickers having 2.5 DoF pattern attached on a standalone-type trackpad (magic trackpad2, Apple). The GND electrodes are connected to the side of the trackpad. It realizes easy setup for hand-held operations similar to game controllers. The hand-held style is also considered to be effective for portable game devices with a touchscreen or tablet PCs.

Controller for a Tabletop. When a user operates a large-sized touch display, he/she has to perform large arm movements. Ohmic-Sticker is also adaptable for tabletop-type touch surfaces, and allows a user to operate with a small finger movement even on large surfaces (Fig. 10 (f)). To realize this, we used a Wacom Cintiq 22HD tablet. The Wacom Feel Multi-Touch API⁵ provides capacitive raw images.

CONCLUSION

We proposed a force-to-motion-type input device to realize various types of force-sensitive inputs by simply attaching it to commercial touch surfaces. The FSR-based structure enabled thin form factors and battery-less operation with low cost. We reported a series of investigations on the design requirements for Ohmic-Sticker and implemented prototypes of Ohmic-Sticker. Next, we conducted a performance evaluation of our prototype. The performance of Ohmic-Sticker yielded 79 % throughput of TrackPoint. Considering the current basic implementation, the result showed promising feasibility as a pointing device. Finally, we described a variety of attractive applications and use cases, including a variation to improve Z-axis operations (Flip-Flop Sticker). We believe, this paper will be a promising reference for developing a physical interface used on “capacitive touch surfaces”. We presented a part of this work in ACM CHI'19 LBW [16].

⁵<http://wdnet.jp/library/feelmulti-touch/wacomfeelmulti-touchfaq>

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