Magnetact: Magnetic-sheet-based Haptic Interfaces for Touch Devices

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ABSTRACT

We describe a method for rapid prototyping of haptic interfaces for touch devices. A sheet-like touch interface is constructed from magnetic rubber sheets and conductive materials. The magnetic sheet is thin, and the capacitive sensor of the touch device can still detect the user's finger above the sheet because of the rubber's dielectric nature. Furthermore, tactile feedback can be customized with ease by using our magnetizing toolkit to change the magnetic patterns. Using the magnetizing toolkit, we investigated the appropriate size and thickness of haptic interfaces and demonstrated several interfaces such as buttons, sliders, switches, and dials. Our method is an easy and convenient way to customize the size, shape, and haptic feedback of a wide variety of interfaces.

CCS CONCEPTS

• **Human-centered computing → User interface toolkits**; *Haptic devices.*

KEYWORDS

Magnet; haptic; interface; touch display; rapid prototyping; tangible; DIY;

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1 INTRODUCTION

A vast amount of information is inputted into mobile devices every day by using finger gestures such as tapping, swiping, pinching-in, and pinching-out. When we input something through a touch screen, we usually keep our eyes on the screen to see where the buttons are. However, mobile devices are also being used as controllers of digital devices, including drones [27], robots [21], and even cars [20]. When you operate an object like a drone with a mobile device, you might not be able to maintain your gaze on the buttons displayed on the screen. Because you have to watch the controlled object in order to see that the input goes well. Therefore, as the importance of gazing at the control target increases, the importance of haptic feedback from touch interfaces also increases.

Usually, gadgets are manipulated with a tangible controller with physical feedback. An aircraft cockpit, the controller of a radio-controlled toy, and gaming pads are good examples. There have been various studies on using touch devices with physical interfaces [3, 12, 23]. However, these works are not designed for rapid prototyping. They require the user to have skills or costs for creating an appropriate physical interface with haptic feedback. There is thus substantial room for improvement aimed at rapid design of touch interfaces.

Here, we propose a sheet-like interface that enables designability of haptic feedback on a touch display (Figure 1). Since the main part of the interface is a magnetic rubber sheet, it can be created in various sizes and forms. In addition, the haptic feedback can be rapidly customized using our magnetizing toolkit. With this method, various interfaces such as buttons, switches, sliders, and dials can be created easily and inexpensively.

The contributions of this research are as follows:

- Development of a haptic interface prototyping method based on magnetic sheets and conductive material.
- Exploration of the appropriate size and thickness of magnetic sheets for touch detection.
- Demonstration of a magnetizing tool and several types of haptic interface.

2 RELATED WORK

A wide variety of digital devices can now be controlled by touch devices [20, 21, 27]. When operating a drone or robot, it is important to gaze at the control target; this in turn raises the importance of haptic feedback from the interface. Haptic

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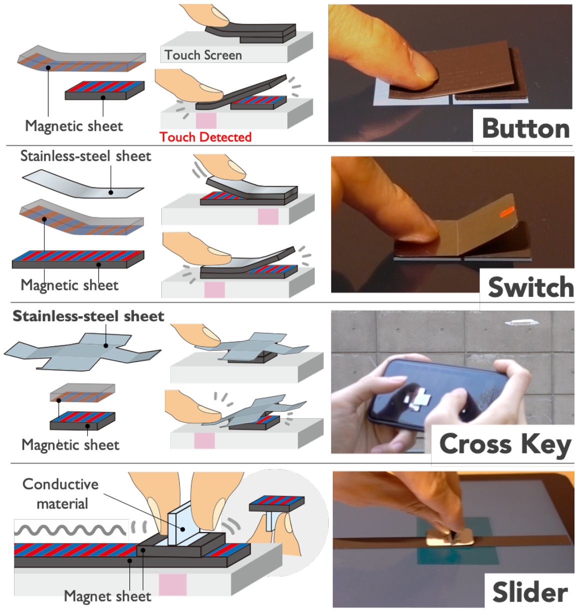

Figure 1: Magnetic-sheet-based haptic interfaces. The shapes, sizes, and haptic feedback of various switches, cross keys, and sliders can be designed and modifieon

feedback from buttons displayed on touch screens has been a subject of interface research for a long time [2, 15, 18]. Today, virtual haptic technology that uses vibration to convey the click feeling (Vibro-tactile technology) [8, 10, 17] has reached a practical level. For example, several mobile devices have vibration actuators behind a button to present haptic feedback instead of physically moving it down when it is pressed. Haptic feedback delivered by vibration is especially useful for customizing the haptic feeling of pushing a button [10, 17]. The user can change the texture of the feedback by configuring the settings. However, vibration is not suitable for presenting where the button is or what the shape it is. It is also not suitable for expressing haptic feedback from multiple buttons.

A better idea would be to use a tangible user interface (TUI) [9] for touch devices to control digital gadgets. The marketplace has many kinds of mobile accessories such as buttons, analog joysticks, triggers, and grips for mobile games [5, 6]. Meanwhile, researchers in human-computer interaction have devised many methods that place passive materials on the touch screen and use them as tangible interfaces [7, 12, 13]. An advantage of TUIs is that users can manipulate them rapidly and finely [3, 22, 23]. This would be beneficial when the user controls a digital gadget. Moreover, the touch sensors can be used to recognize the position, size, orientation of the passive materials [4, 12, 13, 22, 26].

Although users can control digital devices by manipulating tangible objects, a touch interface is still a very limited prototyping platform. It still seems difficult to use touch interfaces to design a variety of haptic feedbacks. In fact, most approaches exploit the elasticity and rigidity of materials or use commercially available physical buttons to present tactile feedback.

Meanwhile, for customizability of haptic feedback, magnetic force has been used for various haptic technologies. Bump Ahead [25], and Mechamagnets [29] are variable tactile feedback by using permanent magnets. Polymagnet [14] and Magnetic Plotter [24] invent computational magnetization methods of permanent magnets and provide physical tools with haptic feedback. Magneto-Haptics [16] is a computational estimation method of haptic texture using several small magnets. Particularly, for customizing haptic feedback, Magnetic Plotter [24] makes use of the idea that the tactile sensation can be controlled by magnetic patterns and showed that it is possible to magnetize complex magnetic patterns with a plotting machine that can be used in the home. These technologies make it easy to construct haptic interfaces. They require no technical skill or expensive equipment for designing tactile feedback.

However, a plotting machine is not a good way of tinkering with physical interfaces. Tangible interfaces are often structural and tridimensional, while most plotter machines can only magnetize sheet-like materials with flat top surfaces. A small plotting machine cannot magnetize something more than 2 mm thick. On the other hand, a hand-held magnetization tool can easily magnetize three-dimensional objects and large surfaces such as walls and floors. It does not require the series of tasks that a plotting machine requires, such as cutting, disassembling and arranging the parts. This freedom enables creators to concentrate on editing the tactile feedback. As the previous rapid prototyping methods proposed [19, 28], it is important to reduce the cost and time for one cycle of creation. For this reason, we invented new haptic interfaces and tools that can easily be used to design, modify, and erase haptic feedback on demand.

Here, we propose Magnetact, consisting of a sheet-like interface and magnetizing tools for easy-to-design haptic feedback. With Magnetact, various haptic interfaces can be created at a low cost and the haptic feedback of each interface can be changed with ease. The user can rewrite the magnetic patterns manually by using the magnetizing tools (Figure 2) as many times as needed until the desired haptic feedback is created. This easy-to-design haptic interface prototyping method encourages people to create a tangible haptic interface for ordinary touch devices by using magnetic sheets. In this study, we investigated the appropriate thickness and size with which to apply the magnetic tactile technique to touch devices and developed several haptic interfaces by using our technique.

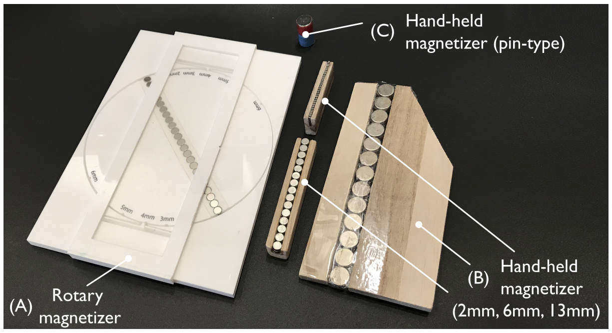

Figure 2: Magnetizing toolkit of Magnetact.

3 MAGNETACT

The basic composition of the sheet-like tangible interface is simple: magnetic rubber sheets and conductive materials (see Figure 1). Since magnetic rubber is a soft material, it is easy to cut a sheet of it into a shape that fits the visual interface of any mobile application. This feature allows users to prototype haptic interfaces rapidly.

The magnetic sheet is also the core element of haptic feedback. Specific magnetic patterns on the surfaces of two magnetic rubber sheets generate magnetic attractive/repulsive forces between the sheets. When a user moves one of the magnetic sheets, he/she will feel tactile feedback corresponding to the magnetic patterns. This is the magnetic haptic technique used in Magnetic Plotter [24]. Moreover, with the magnetizing toolkit we developed, the magnetic pattern can be changed with ease even without a plotting machine.

Magnetizing Toolkit

Here, we describe the magnetization of magnetic sheets. Tactile feedback can be customized by using the magnetic patterns of the magnetic sheet, and a magnetic rubber sheet can be magnetized by applying a strong magnetic field and can keep the arrangement of the magnetized magnetic poles. According to Magnetic Plotter [24], magnetic rubber sheets can be magnetized with a tiny neodymium magnet with a surface flux density of 350 mT. However, it is difficult to draw even straight lines with the same pitch manually because the magnetic field cannot be seen, and if the accuracy drops, the haptic feedback will be weakened greatly. Therefore, we invented handy magnetizing tools that can accurately magnetize stripes even without visualizing the magnetic field.

Rotary magnetizer. In our method, in the middle of the rotary magnetizer (Figure 2, A), neodymium magnets 6 mm in diameter and having surface magnetic flux density of 382 mT are arranged in a line on a turntable. When the magnetic sheet is slid over the magnet line, a magnetized stripe pattern will form on the surface of the sheet (Figure 3, a). Furthermore, by turning the turntable part of the rotary magnetizer, the line of magnets rotates. As a result, the pitch of the magnetizing stripe changes, and thus, the magnetized haptic feedback from the sheet can be modified (Figure 3, b).

When magnetizing 1 - 2 mm pitched striped magnetic pattern using the rotary magnetizer, the rotation angle should be more than 60 degrees and the stripe pattern is magnetized only by the edge of the neodymium magnets. Since the surface magnetic flux density is less than 350 mT at the edge of the magnets, the magnetic sheet cannot be fully magnetized and the haptic feedback becomes weaker. This means the rotary magnetizer is good for magnetizing 3 - 6 mm pitched stripes. For magnetizing 1 - 2 mm pitched stripes, it is better to use magnetizing tools with neodymium magnets 2 mm in diameter.

Hand-held magnetizer. We also have constructed several hand-held magnetizers incorporating magnets of various sizes (Figure 2, B, C). Since these can be freely moved by hand, the freedom one has in designing the magnetizing pattern becomes very large (Figure 3, c-g). For example, it is possible to combine two mutually orthogonal magnetic stripes (Figure 3, f). By magnetizing the magnetic stripe pattern on half of a magnetic sheet and magnetizing a different-pitched magnetic pattern the 90-degree-rotated magnetic stripe to the other half of the sheet, the magnetic sheet can present different haptic feedbacks in different directions (Figure 3, h). Moreover, it is easy to erase (Figure 3, g), rewrite, or modify the feedback freehand.

Touch Detection vs Haptic Presentation

Here, we describe the dielectric behavior of the magnetic sheet. Magnetic rubber is not a conductive material, but rather a dielectric material. When a material with high relative permittivity is placed between the electrostatic capacitive sensor and the hand, the material acts like a capacitor such that an electrostatic capacitance will be stored (Figure 4). The charge Q is proportional to the capacitance C when the electric potential V of a touch sensor is constant. The capacitance of a capacitor constructed of two parallel plates both of area A separated by a distance d filled with a material having a relative permittivity ϵ can be calculated as follows:

$$Q = CV = \epsilon \frac{A}{d} V \tag{1}$$

If the amount of charge Q held by the capacitor is sufficient, the sensor detects the contact of the material as the touch of a finger. This is why bananas (which have high relative permittivity) can be used as a stylus pen. According to (1), when a magnetic sheet of appropriate thickness is attached to a capacitive touchscreen, the capacitive sensor can detect the user's finger on the other side of the magnetic sheet thanks to

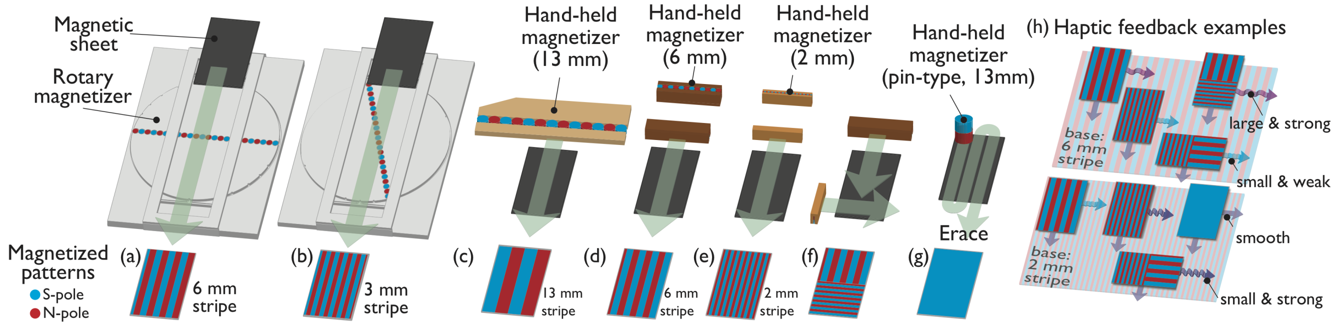

Figure 3: The magnetizing tool can write a stripe magnetic pattern of different pitch on demand. The haptic sensation can be changed within seconds. The user can modify the magnetic patterns until the desired haptic feedback is achieved.

the sheet's dielectric behavior. However, there is a trade-off between touch detection and strength of the tactile feeling. For the same magnetic material, thicker magnetic sheets can generate stronger magnetic force. Therefore, we performed a measurement that clarified the maximum magnetic sheet thickness at which a capacitive touch display can detect a touch on the sheet.

Maximum Thickness for Touch Detection

We prepared magnetic-sheet test pieces of different thicknesses and performed measurements on them. The magnetic sheet (AFG-20100, ProMAG Products.) was about 0.7 to 0.9 mm thick with adhesive on one side. Test pieces thicker than 1 mm were prepared by overlaying the sheets using the adhesive.

The touch detection capability of the capacitance sensor depends on the touch device. Here, we chose to test an iPhone7 (A1779, Apple), one of the most common devices. According to Apple's human interface design guideline [1], the minimum area required to construct one button is a touchable square of 44 x 44 px, which is about 7 mm x 7 mm. Following that, we prepared 10 mm x 10 mm sized test pieces.

Each test piece was magnetized with a magnetic pattern with a 2 mm pitched stripe on its surface. As described in Magnetic Plotter [24], the strongest holding force between two thin magnetic sheets is when they have a magnetized stripe pattern with a 2-mm pitch. Hence, we magnetized a 2-mm pitch stripe pattern with the hand-held magnetizer, which contained a neodymium magnet 2 mm in diameter with a surface magnetic flux density of 372 mT.

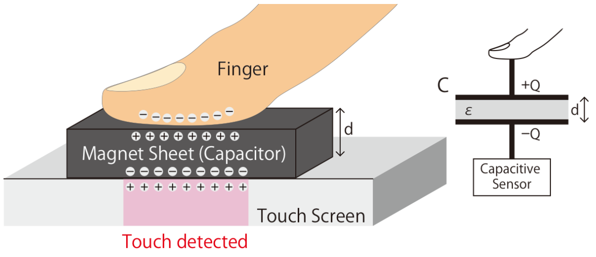

Figure 4: The capacitive sensor can detect a finger above the magnetic sheet due to the sheet's dielectric nature.

Then, each test piece was attached to the center of the display by using the adhesive of the magnetic sheets. We conducted 100 touch detection trials on each test piece, with the device connected or not connected to the power supply. We recorded the number of successful touch trials.

We also measured the maximum surface magnetic flux density of the layered magnetic sheets by using a gauss meter (Kanetech Co., Ltd., TM-801). The results are shown in Figure 5. Although the magnetic flux density increases with thickness, the touch detection rate falls sharply when the thickness of the magnetic sheet is more than 2 mm. From these results, we can say that the guideline for creating this interface is a magnetic sheet thickness of 1.8 mm or less to ensure the touch detection of the device.

Magnetic Force for Tactile Feedback

Next, we investigated how much magnetic attractive force acts between two magnetic sheets each with a thickness of 0.9 mm (total thickness of 1.8 mm) and how well the click feeling can be presented with them. As an example, we chose a standard tact switch (TSHA-T, Top-up Industry Corp.), which contains a dome-shaped metal plate that generates a click response when a load of 120 − 140 gf is applied. On the basis of this value, we clarified the minimum size for a button-type interface that conveys a click feeling equivalent to the actual tact switch.

We constructed the system shown in Figure 6. A magnetic sheet was set horizontally on a flat plastic base with adhesive and another sheet was placed on it. The upper sheet was 10 mm longer than the lower one. We set a digital force gauge (ZTS-2N, Imada Co., Ltd.) in the center of the extended part

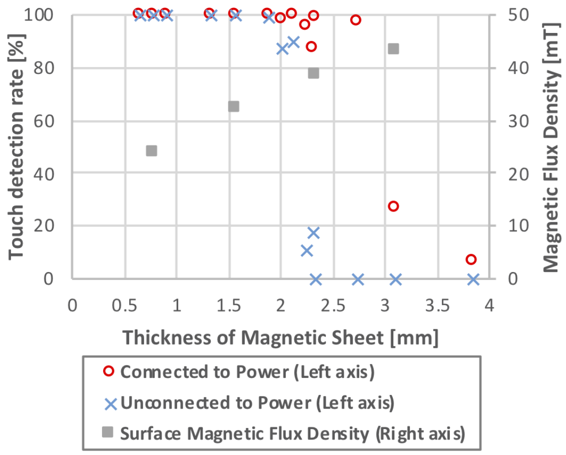

Figure 5: Results of touch detection test. 1.8 mm seems to be the maximum thickness for an iPhone7 to be able to detect a touch.

of the upper sheet and pushed it vertically downward and recorded the maximum push force until the upper sheet detached from the bottom one. The measurement was done with magnetic sheets with widths W of 10 and 20 mm and lengths L from 10 to 40 mm.

Figure 7 shows the results, which indicate that a sufficient magnetic force was presented with the proper sized magnetic sheets. For presenting an equivalent click feeling as the physical button, it requires more than 25-mm length with 10-mm width sheet, and 19-mm or more for 20-mm width sheet.

However, for lengths larger than 25 mm, the magnetic sheet seems to become detached more easily. The attractive force per unit area **m** can be calculated from the following equations. It is considered that the magnetic sheet peels off when the rotational moment around point O due to a force **F** applied to the measured point P exceeds the rotational moment due to the attractive magnetic force **N** of the two magnetic sheets.

$$\mathbf{F} \cdot PO = \mathbf{N} \cdot \frac{L}{2} \tag{2}$$

$$\mathbf{N} = \mathbf{m} \cdot W \cdot L \tag{3}$$

$$\mathbf{m} = \mathbf{F} \cdot \frac{PO}{(W \cdot L \cdot \frac{L}{2})} \qquad \because (2) and (3) \tag{4}$$

For example, the attractive force per unit area **m** is about 20 gf/cm2 for 10-mm-wide by 20-mm-long sheets, whereas **m** is only about 11 gf/cm2 for 10-mm-wide by 40-mm-long sheets. This difference seems to be due to the flexibility of the magnetic sheet (Figure 8). The upper sheet which is bending and deforming cannot hold the bottom sheet with the strongest force.

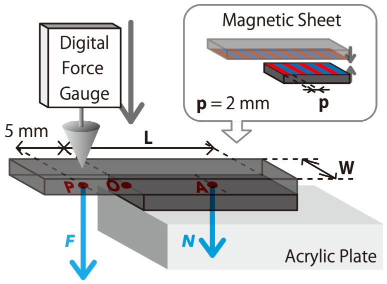

Figure 6: Measured structure.

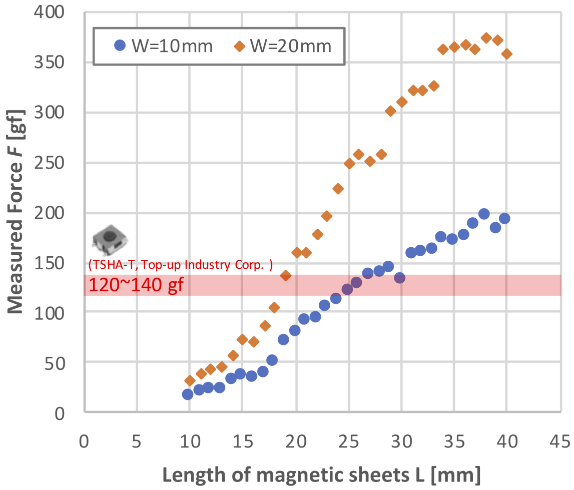

Figure 7: Measured force.

To determine that this is so, we prepared additional test pieces. We fixed a 0.25-mm-thick stainless-steel sheet on the top of the magnetic sheet as reinforcement and performed the same measurements as described above. Although the rigidity of stainless-steel prevents the magnetic sheet from deforming enough, the stainless-steel sheet still can be cut with scissors and bent with pliers or by hand.

Figure 9 shows the magnetic force per unit area. Accordingly, the stainless-steel sheet supported the interface, thereby providing stronger force feedback. In particular, the force per unit area was much stronger in the test pieces with a width of 20 mm and length of 20 mm or more.

4 INTERFACE APPLICATIONS

The above experiments indicated several things. First, the thickness of the magnetic sheet from the touch screen to the point of touch should be within 1.8 mm. Touch detection performance can be improved by using a thinner magnetic sheet. Second, if there is a layer of air between the magnetic sheets and the touch screen, touch detection is difficult since the relative permittivity of air is very low. Therefore, care must be taken not to create gaps between the sheets. Third,

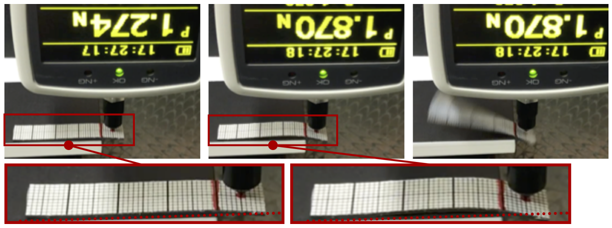

Figure 8: Deformation of a test piece during experiment. Distortion occurs on the right before peeling off.

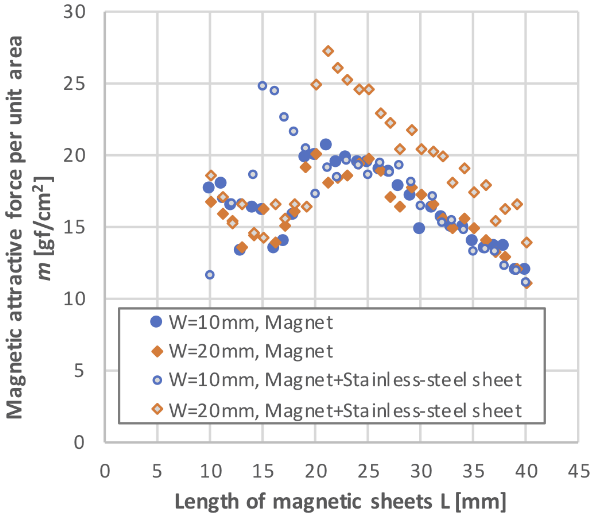

Figure 9: Magnetic force per unit area. The stainless-steel sheet reinforces the magnetic sheet for providing stronger force feedback.

by attaching a stainless-steel sheet to the magnetic sheet, the interface can be made more rigid and the haptic feedback stronger. Stainless steel is also a conductive and ferromagnetic material. Therefore, a sheet made from it can be used not only as reinforcement but also as a touch detectable part and magnetic absorption part. Next, we created examples of haptic interfaces incorporating what we learned.

Buttons, Switches, and Cross Keys

By applying what we learned from designing a button Magnetact that presents a sufficient click feeling, we created various haptic interfaces such as switches and cross keys (Figure 1). The size and shape can be customized with ease.

Sliders

We made a slide switch Magnetact which can change its bumpy feeling with ease. Moreover, a combination of two magnetic stripes creates an interface that gives a zipper-like haptic feedback (Figure 10). The longitudinal magnetization stripe presents the rail-like feedback of the zipper slider and the lateral magnetization stripe presents the toothtexture.

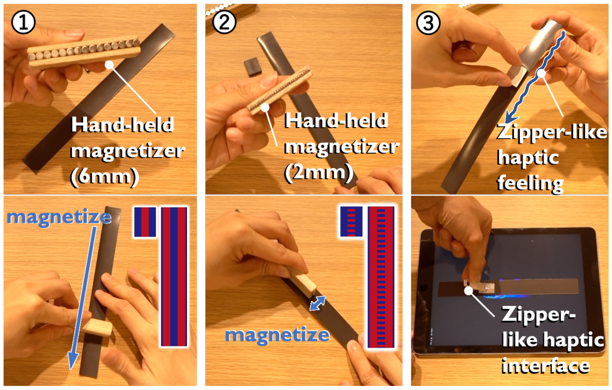

Figure 10: A zipper-like haptic interface. The longitudinal magnetization stripe presents rail-like feedback, and the lateral magnetization stripe presents a tooth texture.

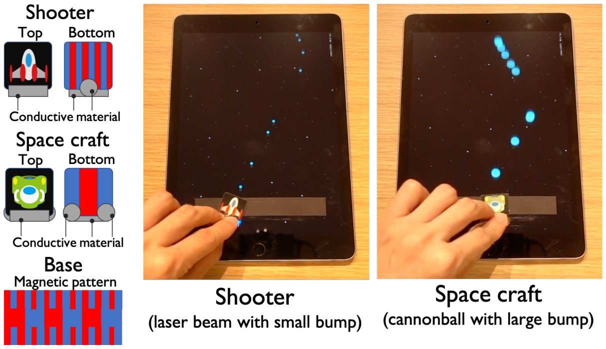

Figure 11: This design with conductive materials links the visual image, sound, and haptic feedback presents them as one event.

Moreover, the slider Magnetact can be used as a tangible interface for games since our methodology is good for linking the visual image, sound, and haptic feedback and presenting them as one event (Figure 11). We prepared two slider knobs and gave them different conductive patterns and different magnetic patterns. When the conductive pattern of the knob that presents a fine haptic texture is detected by the device, the software presents a sharp sound and displays a laser-beam-like shot. On the other hand, when the conductive pattern of the slider knob that presents a large haptic texture is detected, a drum sound is presented and a cannonball shot is displayed. By designing the arrangement of the conductive patterns, the position, direction, and unique ID of the interface can be used for interactive input.

However, this method is not suitable for dynamic tactile presentations such as shock effects in video games or message notifications. For haptic presentations of this sort, it may be easier to output vibrations from electromagnets or speakers.

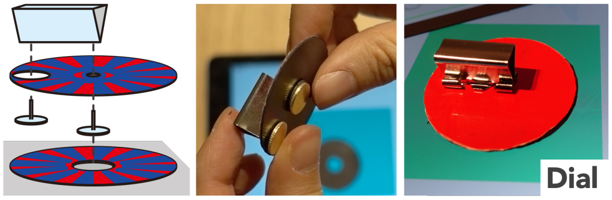

Figure 12: The construction of the dial Magnetact.

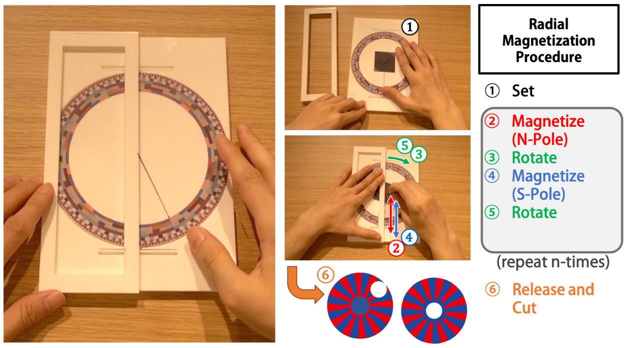

Figure 13: The radial magnetic pattern for the dial Magnetact can be magnetized using the rotate magnetizer.

Dials

We created a dial-type Magnetact. The disk-shaped magnetic sheets with radial magnetic patterns (Figure 12) present 12 steps of click feelings when the knob is rotated. By combining conductive materials, the position and orientation of the dial Magnetact can be estimated from the touch detection.

The dial Magnetact knob is made of a binder clip and metal push pins, and the clip bridges the pushpin fixed in the center of the bottom sheet and the other pushpin fixed at the edge of the upper sheet. When the dial is rotated with the knob, the two touch points can be detected at the same time by the touch device. From these two positions, it is possible to calculate the position and rotation angle.

Moreover, the radial magnetic pattern for the dial Magnetact can also be magnetized with the magnetizing tool (Figure 13). The radial magnetization mode is set by turning the center turntable part of the magnetizing tool over. A magnetic sheet is put on the center pin, and the S and N poles are alternately magnetized with a pin-type hand-held magnetizer while turning the turntable along with the scale printed on the edge of the turntable. The radial pattern can be magnetized in about 3 to 7 minutes.

5 DISCUSSION

This research is in the engineering domain. Since the main topic of this paper is a new haptic interface prototyping method, it does not deal with user tests and instead focuses on methodology. Here, we will discuss the limitations and characteristics of our technique as a rapid prototyping method.

Processing time

Using our magnetizing tool, the magnetization of a simple striped pattern can be completed within few seconds, and the tool can rewrite the stripes again and again. By contrast, the Magnetic Plotter method takes a few minutes to magnetize even a simple striped pattern, because it uses only one tiny magnet for magnetization. For rapid prototyping, any reduction in processing time is an advantage.

Transparency and color of the interface

Color is an important aspect of customization. However, the magnetic sheet is opaque. When the interface is attached to a touch screen, the images displayed under the sheet cannot be seen. Using a transparent magnet [11] instead of black rubber material may solve this problem. However, it will probably be more than a few years before such materials become commercialized. For now, if the image under the magnet is a important, a good solution is to cut out the sheet part of the interface. Similarly, when a stainless-steel sheet is attached to the top of the magnetic sheet, its color cannot be changed easily. If the stainless sheet is covered with a colored vinyl sheet or ink, conductivity drops to zero and touch detection will not work properly. We need a method to color and print specific images on conductive surfaces. These coloring problems remain as future work.

6 CONCLUSION

We presented a very simple rapid method of prototyping haptic interfaces that uses magnetic rubber sheets and conductive material. The interface is very simple, and users can customize not only the size and shape, but also the haptic feedback of a tangible interface with ease. In particular, tactile feedback can be customized with ease by using simple magnetizing tools to change the magnetic pattern of the magnetic sheet.

We also investigated finger touch detection and clarified the appropriate thickness and size for exhibiting a click feeling. On the basis of the results of the investigation, we developed several prototype interfaces such as buttons, sliders, switches, cross-keys, and dials. We also implemented several magnetizing tools for the interfaces. With these tools, the magnetic sheets can be magnetized with ease, and we demonstrated that magnetic stripe patterns with an arbitrary pitch can be easily created. We also demonstrated touch interactive applications using these stripe patterns.

By using our method, creators can easily and economically design and modify the shapes, sizes, and tactile feedback of haptic interfaces for touch devices. This will encourage rapid prototyping and personal fabrication and workshops.

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