FingerFlux: Near-surface Haptic Feedback on Tabletops

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ABSTRACT
We introduce FingerFlux, an output technique to generate near-surface haptic feedback on interactive tabletops. Our system combines electromagnetic actuation with permanent magnets attached to the user's hand. FingerFlux lets users feel the interface before touching, and can create both attracting and repelling forces. This enables applications such as reducing drifting, adding physical constraints to virtual controls, and guiding the user without visual output. We show that users can feel vibration patterns up to 35 mm above our table, and that FingerFlux can significantly reduce drifting when operating on-screen buttons without looking.

ACM Classification: H5.2 [Information interfaces and presentation]: User Interfaces.—Haptic I/O.

General terms: Design, Human Factors, Experimentation

Keywords: Haptic feedback, Magnets, Actuation, Interactive Tabletops

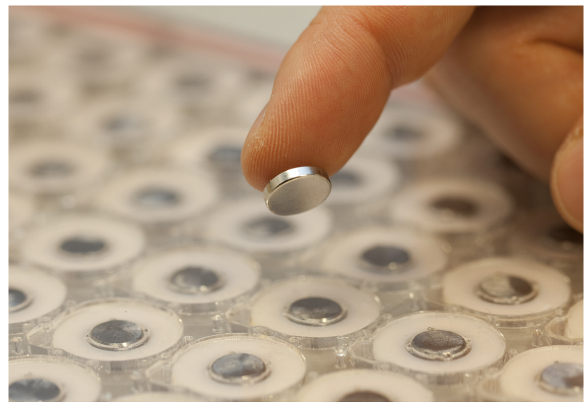

Figure 1: FingerFlux provides attraction, repulsion, vibration, and directional haptic feedback on and near the surface using electromagnets in the table and a permanent magnet attached to the user's finger.

INTRODUCTION

Touchscreens allow users to directly manipulate objects on the screen with their fingers. This interaction heavily depends on the user's visual perception of the hand [8] and visual feedback from the screen [27]. Yet, there are situations in which vision is not available, such as entering text on a touchscreen while reading it off a piece of paper, or rejecting an incoming phone call while driving. When the visual sense is taken away, although the direction of hand movement is still accurate [5], the touches gradually drift from the target [4]. Using suitable haptic feedback reduces those errors, lowers subjective workload [17], increases attention [2], and improves motor learning [13].

The introduction of haptic feedback on touchscreen devices has received much attention [1, 11]. However, a common property of most approaches is creating *a posteriori* feedback: the haptic feedback begins *after* the surface is touched. To maintain input efficiency, drifting has to be compensated by algorithms that interpret uncertain input [20]. However, if the user is drifting too much, e.g., beyond the boundaries of a control she wants to press, there is no haptic feedback to realign her fingers anymore.

In this paper, we present a system that allows users to feel haptic feedback when hovering above the table, i.e., *before* they touch the surface. Our system is based on electromagnetic actuation [18, 25] in combination with permanent magnets attached to the user's hand. By attracting or repelling these permanent magnets, we create haptic feedback over a distance and guide the user when she approaches the surface.

After giving an overview on related work, we will explain our prototype design and describe example applications. Moreover, we provide evidence that users can feel haptic feedback above the table and that our technique significantly reduces drifting when operating buttons without looking. The paper closes with a discussion about limitations and a conclusion.

RELATED WORK

There are different classes of techniques that improve haptic feedback on touchscreens. The first generates haptic feedback *on the surface*. One of the early approaches are pin displays, e.g., [14], that display Braille characters by moving thin rods upwards from the surface. SmartTouch [12] is an electrocutaneous display which pulses small currents to the finger to generate haptic feedback. More recently, TeslaTouch [1] uses electrovibration to dynamically change perceived surface friction. MudPad [11] uses electromagnets to change the viscosity of magnetorheological fluids in the surface. These techniques can only create feedback while the user touches the surface.

Tangible user interfaces are physical objects that are used to represent and manipulate virtual data. They can provide rich haptic feedback and physical constraints [26]. Furthermore, they can act as mediator for dynamic haptic output [15, 24]. However, they have to be placed on the table explicitly, consume real estate, and are harder to use on small or non-horizontal surfaces.

Stationary devices like the PHANTOM [16] or Maglev Haptics [6, 23] can provide 3D haptic feedback to a user's fingertip. Similarly, exoskeletons attached to the user's arm [3], gloves [29], and electrodes that directly stimulate muscles in the user's hand [22] can create haptic feedback *above the surface*. Although these methods are effective in providing a priori feedback, stationary devices are difficult to use on interactive tables while the others require users to wear complex actuation systems or create local vibration feedback only. Arrays consisting of air-jet [21] or ultrasound emitters [10] create a 3D sensation in the air. Yet, these displays are limited in resolution and can only create a repulsion feedback. SenseableRays [19] uses a lightweight actuator, attached to the user's fingertip, which converts structured light to tactile patterns. Still, the proposed system can only produce vibration feedback.

Our technique is based on magnetism, which has been investigated for both output and input previously. On the output side, the seminal system Actuated Workbench uses an array of electromagnets to move magnetic pucks on a tabletop [18]. More recently, Madgets [25] supports actuating complex tangible controls and provides techniques to push physical objects in the vertical direction. On the input side, Hook et al. [9] employ an array of coils for detecting ferrous objects on a tabletop. Our hardware design is also inspired by Abracadabra [7] which tracks a magnet attached to a finger for precise input on small-screen devices.

The body modification artists has also explored the addition of a *magnetic sixth sense*. People implanted or glued magnets to their fingertips to be able feel electromagnetic fields. Furthermore, Wishnitzer et al. reported that gamblers used subcutaneous magnets to control dice containing magnets [28].

In contrast to previous approaches, FingerFlux can generate repulsion, attraction, vibration, and directional feedback on and above the surface, without mounting bulky equipment on the user's hand.

PROTOTYPE DESIGN

For electromagnetic actuation, we used the design of the Madgets table [25]. A discrete grid of 19×12 electromagnets allows for synthesizing a 2D matrix of magnetic fields. Each magnet (19.5 mm diameter $\times$ 34.5 mm height) contains 3,500 turns of enameled copper around an iron core. We drive the magnets at 40 V DC and 255 mA. Strength and polarization of each electromagnet can be controlled individually from software. A backlit LCD panel on top of the array provides graphical output.

Our system uses electromagnetic fields to generate feedback *beyond* the surface. Similarly to the input technique Abracadabra [7], we attached a permanent magnet to the user's finger (Fig. 1). Electromagnets in the table create magnetic fields that attract or repel these permanent magnets. Being attached to the user, they directly pass their force to the user's skin. We can, therefore, create haptic feedback in the near-surface volume above the table. Note that users do not have to move their fingers to feel the feedback.

For our prototype, we attach two cylindric neodymium magnets (10 mm diameter $\times$ 2 mm height) below the finger tip of the user's index finger using elastic tape. We observed that a rigid tape reduces the haptic sensation in the finger. Note that the two magnets could also be replaced with a single thicker one. For consistency, the same pole of the magnet always faces away from the finger surface.

It is also possible to generate multi-finger feedback by attaching magnets to more fingers. We created a prototype glove with magnets fixed to multiple parts of multiple fingers. However, those magnets attracting and sticking to each other made the glove difficult to wear. Yet, this effect is less severe if magnets are only put on the fingertips.

APPLICATIONS

Using our setup, we can apply two basic forces to the user's finger: attraction towards and repulsion away from one or more electromagnets beneath the surface. We prototyped a set of applications using a combination of these forces. In the following, we explain these applications, beginning with those requiring single magnets only to those that involve an entire array.

A Priori Feedback in Near-surface Interaction

Our technique allows users to feel electromagnetic force fields when hovering above the surface. Using a single magnet with repelling magnetic field, a designer can model a haptic bump. This simple technique can be used to let users feel the table interface without looking or to emphasize the state of an on-screen object. For example, a strong repelling force can signify a UI element which is currently unavailable like an inactive button. When the polarization of an electromagnet is quickly reversed repeatedly, the user feels a vibration pattern when approaching the electromagnet. Those patterns could indicate a system event or warn users before they trigger critical operations, e.g., an "Exit without saving" button could emit a vibration signal to avoid accidental presses. Beyond that, magnetic fields could be exploited as private output channel that only users wearing permanent magnets could perceive.

Reducing Drifting

When users interact with touch devices while focusing on different tasks, they tend to drift away from their targets [4, 15]. Unlike approaches that try to interpret uncertain input, e.g. [20], we can use attracting forces to realign the finger's trajectory before it touches the surface. One example is virtual buttons. To reduce drifting, we can attract the user's finger to each button's center. Repelling forces around the center increase this effect by pushing the finger away from the control's boundary (Fig. 2a). This feedback re-

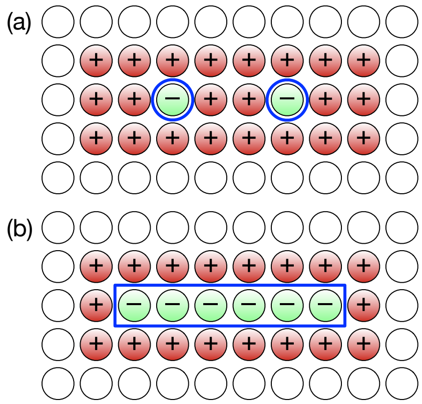

Figure 2: Actuation scheme with idle (white), attracting (green) and repelling electromagnetic fields (red). (a) Buttons (blue circles). (b) Slider (blue rectangle).

duces errors caused by accumulated drifting as will be shown in the Evaluation section. It is also straight-forward to apply this technique to transfer the snap-to-grid functionality known from GUIs to tabletops. For example, the table can attract the user's finger to points in a virtual grid when she approaches them.

Moderate Physical Constraints

By arranging attracting and repelling magnets in lines, we can create moderate physical constraints on the surface without using any physical widget, e.g., a virtual slider may use the actuation scheme in Fig. 2b. The user can slide to the left end or the right end smoothly. If she moves to the front, to the back, or beyond the endpoints, she needs to force her finger through the repelling magnetic field. Together with the ability to change these schemes dynamically, FingerFlux enables a richer interaction design. E.g., the size of this haptic slider could be changed on the fly, or an application could dynamically turn on detents by activating magnets beneath points of interest more strongly than other magnets.

Guiding the User

The Actuated Workbench [18] shows that electromagnetic arrays can create horizontal forces to move objects on tabletops. We can use the same method to create *directional* haptic feedback, e.g., if the user hovers her finger above the table and a nearby magnet is activated, her finger is either attracted towards or repelled from the target, depending on polarization. This allows application designers to guide the user across the table. An example is teaching gestures, or helping users with visual impairments to find an object on the screen.

Rendering Objects

An entire high-resolution magnet array would allow designers to even render lines and basic shapes using repelling magnetic fields. This could, e.g., help blind people to sense geographical information like a city map which otherwise would not be available on a touchscreen. By creating repelling fields with various strengths, the table could also simulate 2.5D objects in form of an elastic height map. Note that the array could only render smooth surfaces without sharp features due to the elliptical shape of magnetic fields.

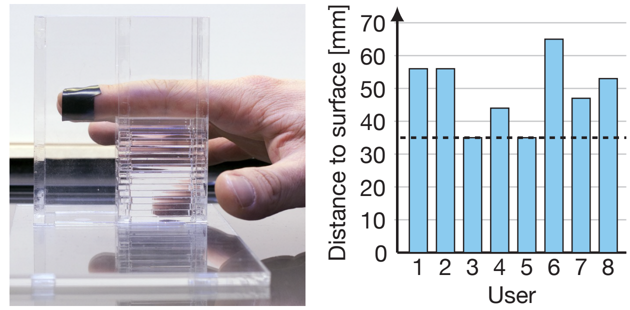

Figure 3: Near-surface haptic feedback test. Left: User test setup. Right: Distances from the surface at which each user reports random vibrations 100% correctly for all 10 trials.

EVALUATION

We conducted two user studies to prove our key contributions. Our first experiment evaluates to which extent FingerFlux provides near-surface haptic feedback. The second one tests if our system can influence input before the user touches the surface.

User Test 1: Height of Near-surface Haptic Volume

In our first user test, we determined the maximum height above the surface at which the haptic feedback can be perceived reliably. We chose a vibration feedback for this test, as our pilot study indicated that vibrations are easier to perceive than constant forces, probably due to the larger peak-to-peak amplitude of the force.

Test Setup. Fig. 3 (left) shows our test setup. An acrylic box which is opened towards the user contains a track for stacking acrylic plates. During the test, the stack of plates supports the finger of the user, so that the finger tip is directly above an electromagnet that we trigger. Each plate is 3 mm thick, except the bottommost plate which amounts to 5 mm. The acrylic plate stack allows us to control the distance from the fingertip to the surface via the number of stacked plates.

Participants. We tested eight users (age: 23–28 years, M = 25.6, SD = 2.10). One was female. All users but one were right-handed.

Procedure. We attached two cylindrical neodymium magnets (2 mm height $\times$ 10 mm diameter each) to the index finger of the user's dominant hand. The distance of the finger from the surface started at 20 mm. In each trial, the user hears two audio beeps, two seconds apart. Between the beeps, the system randomly creates either no signal at the electromagnet beneath the finger or a full-power signal with alternating polarization at 10 Hz. The latter causes permanent magnets at the finger to be attracted and repelled quickly, which can be perceived as vibration. After the second beep, the user reported to the instructor whether or not she felt the vibration. The instructor entered the answer into the software, and started the next trial. After 10 trials another 3 mm plate was placed on the stack, and the test repeated until the height of 65 mm has been tested. In total, each user performed 160 trials (10 trials $\times$ 16 height steps).

The test was double-blind: neither the user nor the instructor could see or hear whether the electromagnet produced a vibration signal or not. For each of the user's answers, the software checks whether it was correct or not. The maximum height that the haptic feedback is reliably sensed at is determined from the minimum of heights in which all users gave correct answers in all 10 trials.

Results. Fig. 3 (right) shows the results. All users were able to detect the vibration signal up to a height of 35 mm. User 6 even reliably differentiated signals up to 65 mm.

Discussion. Our results provide a proof of concept that electromagnetism can provide haptic feedback in a useful area above the surface. The volume is large enough to use the haptic channel as an output when hovering the finger above the surface. Nevertheless, designers should be reminded that the magnetic force attenuates quadratically to the distance from the surface. Accordingly, they should use smaller distances for haptic output.

The intensity of the haptic output and the maximum height depend on many hardware parameters, such as the size of the electromagnets, the voltage applied, the quality and size of the permanent magnets at the user's finger, and the temperature of the magnets. Individual differences between users also influence the maximum height.

User Test 2: Reducing Drifting

In our second study, we evaluated whether or not FingerFlux reduces drifting when pressing on-screen buttons without looking.

Test Procedure. As in the previous test, the user worn two neodymium magnets beneath her index finger of the dominant hand. For precise tracking of the finger, we used a Vicon optical tracking system[1] and glued a single retroreflective marker on top of the fingernail. Two circular buttons (25 mm diameter, 40 mm = 2 electromagnets gap) were displayed on the table surface. Users had to push the left and right button alternately without resting their hands on the surface (Fig. 4, left). The independent variable was the feedback condition:

- In the *non-haptic* condition, we did not create any electromagnetic fields.
- In the *haptic* condition, we created two attracting electromagnetic fields beneath each button center, and repelling fields around them (Fig. 2a).

Users performed both conditions consecutively, starting with the left button in each. Order of conditions was counterbalanced among users to prevent learning effects. Each condition consisted of 14 training presses and 44 measured presses. Each trial was a left button press, except the first press for which users hovered their fingers above the starting position before closing their eyes. We advised users before the training that they had to perform the measured period eyes-free so that they could memorize the movement during the training period. First, the users completed 7 trials in which they were allowed to look at the buttons. Then, they had to close their eyes and perform 22 trials.

[1]http://www.vicon.com

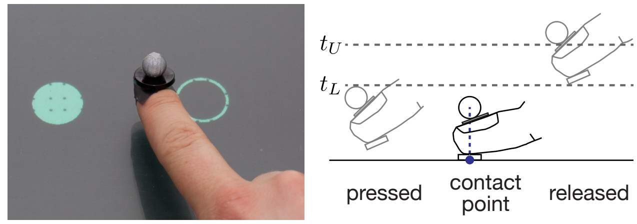

Figure 4: Drifting reduction test. Left: Test setup. Right: Contact point detection with upper (t_U) and lower (t_L) threshold for touch detection .

We measured the presses using the Vicon optical tracking system and a hysteresis thresholding. When the marker on the finger was moved below the lower threshold (15 mm), the button was considered as held down. When the user then moved the marker beyond the upper threshold (17 mm), the button was released. We considered the x-y-projection of the position closest to the surface as the *contact point* (Fig. 4, right). Since this contact point was slightly different among users, we measured the deviation based on the initial contact point of the left button where the user started.

The dependent variable was the *cumulative drift* [4] of the contact points. Following Brown et al., this is the Euclidean distance between the first contact point on the left button and each successive contact point for that button. Brown et al. show that the cumulative drift increases with trial numbers if no haptic feedback is present. We hypothesized that in our haptic condition, the cumulative drift would not increase along with trial numbers.

Participants. We tested 10 users (age: 23–29 years, M = 25.6, SD = 2.17). Two were female. All users were right-handed.

Results. The effect of haptic feedback can be seen from a trace of contact points such as the example shown in Fig. 5. The non-haptic condition is shown in bright red, and the haptic condition is shown in dark green. The arrows show the order of the trials. The contact points in the non-haptic feedback condition gradually drift downward. The contact points in the haptic feedback condition, however, are clustered together and do not show any consistent drifting direction.

As shown in Fig. 6, the increased cumulative drift in non-haptic condition, plotted in bright red, confirmed Brown et al.'s experiment [4], $F(1, 219) = 194.11$, $p < .001$, $r = 0.69$. In the haptic condition, plotted in dark green, however, the cumulative drift did not accumulate, $F(1, 219) = 3.51$, $p = .062$.

Discussion. Our results show that using electromagnetic force fields can significantly decrease drifting when operating virtual buttons in an eyes-free setting. As in the previous test, the attraction to the surface depends on the applied voltage and on the quality and size of the magnets involved. Furthermore, the position of the permanent magnet on the fingertip might influence touch performance. According to Holz and Baudisch [8], users rely on visual features to de-

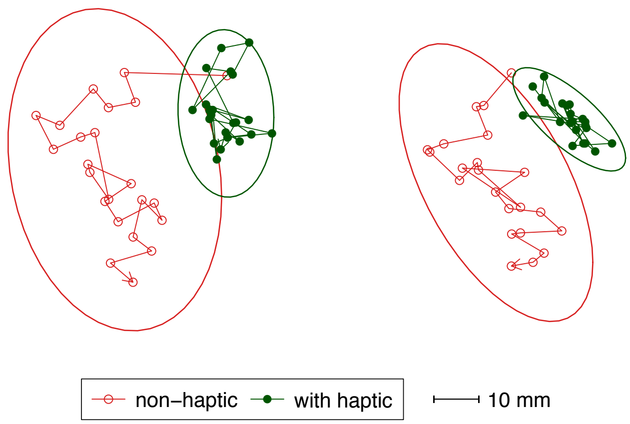

Figure 5: An example of contact points in the eyes-free user test. The ellipses superimpose the 95% confidence level of the normal-probability contours.

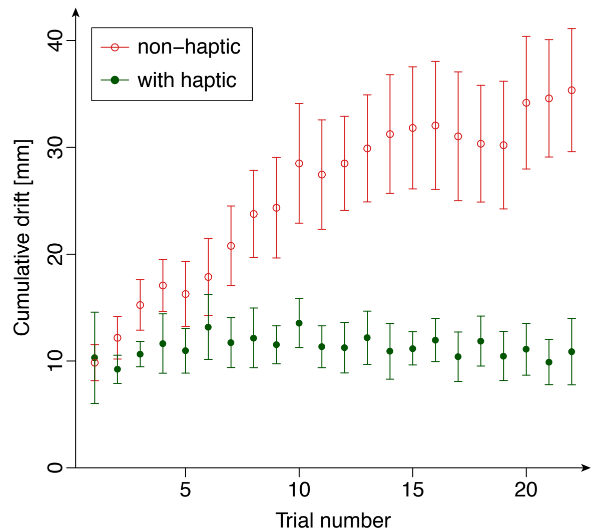

Figure 6: Comparison of drifting with and without haptic feedback. Inter-subject means of cumulative drift in each measured trial. Error bars represent inter-subject SE. Without haptic feedback, drifting increases in subsequent trials. With haptic feedback, it does not increases in subsequent trials.

rive a mental model of where the actual contact point on the surface is. The electromagnet at the button's center, however, attracts the permanent magnets to a distinct position which does not necessarily match the user's mental model. Although this is not an issue in an eyes-free task, the interaction while looking could suffer from interfering visual and haptic models. This should be taken into account when attaching the permanent magnet to the finger.

DISCUSSION

Our prototype involves taping a magnet to the user's fingertip to maximize the perceived haptic feedback. While this preserves most pressure and shearing feedback when touching and dragging on the surface, this specific setup reduces the tactile sensation of the fingertip and might be impractical for ad-hoc use. However, more practical solutions are straightforward, such as wearing a glove or a thimble that places a magnet to the each side of the finger or on top of the fingertip. Also, a less direct input device, such as a stylus, is imaginable. In all cases, users have to wear an additional feedback device. Yet, this limitation can be worthwhile in many applications, e.g., when providing haptic feedback for blind people that could not feel the interface otherwise.

Haptic feedback is most effective when the magnet is hold parallel to the table. Rolling the finger around inverses the perceived force. However, we did not observe this inconvenient posture in our studies. Yet, in cases where tilting finger gestures are considered for input, or where a physical input device is used (e.g., a stylus with permanent magnet attached to its tip), orientation must be tracked, e.g., with an accelerometer, and magnetic fields must be adapted accordingly.

The strength and quality of the haptic experience also depends on the properties of the involved permanent and electromagnets. Beyond that, ergonomic constraints must be taken into account when designing the system. On the one hand, a large neodymium magnet at the user's finger enables strong feedback but may be inconvenient to wear. On the other hand, smaller permanent magnets need a higher electric power consumption for the same haptic effect.

The diameter and space of the electromagnets determine the haptic output resolution. While a smaller diameter allows designers to model smaller virtual controls, this also decreases the power of the electromagnets. A longer electromagnet or a different core material can compensate for this. Also, dynamically modulating the strengths of adjacent electromagnets can increase the haptic resolution. However, this requires precise tracking and high update rates of the electromagnetic array.

Electromagnets become warm when activated over a long time. The warmer an electromagnet is, the higher is its electrical resistance, and, therefore, the lower the force felt by the user. Cooling the array is essential to apply a constant force.

CONCLUSION AND FUTURE WORK

We presented FingerFlux, a system for creating near-surface haptic feedback in tabletop systems. Using electromagnetic actuation with permanent magnets on the user's finger tip, we are able to generate repulsion, attraction, vibration, and directional feedback on and above the table surface. Several potential applications using this feedback were presented. We have shown that the feedback is perceivable in a volume near the surface up to a height of 35 mm, and that it can reduce drifting when users operate on-screen controls in an eyes-free manner.

For future work, we want to explore the perceivable resolution of magnetic actuation patterns on different parts of the hand. We are also interested in evaluating the capabilities of the system to generate multi-finger haptic feedback. From an engineering perspective, we want to iterate practical designs that make wearing a magnet on the hand convenient but also preserve the natural tactile sensation when interacting with touchscreens. Finally, we intend to implement and evaluate applications that employ near-surface haptic feedback to augment productivity tasks.

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