GaussBits: Magnetic Tangible Bits for Portable and Occlusion-Free Near-Surface Interactions

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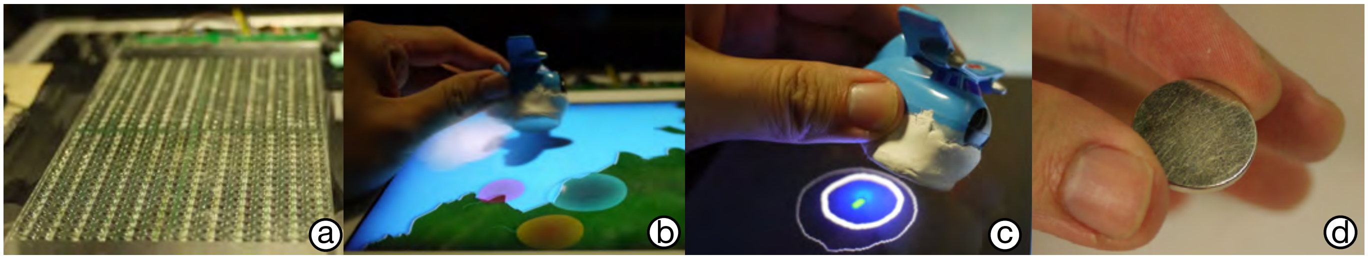

Figure 1. ***GaussBits*** **support occlusion-free tangible interactions on and above the portable display. (a) Magnetic sensor grid for sensing** ***GaussBits*****. (b) The tangible flight simulation,** ***GaussPilot*****, allows users to pilot the flight by setting the orientation of a toy aircraft. (c) Sensed magnetic field image of the** ***GaussPilot*****, from which the 3D position and tilt information can be obtained. (d) Inside the toy aircraft, a magnetic unit is stuffed for sensing.**

ABSTRACT

We present *GaussBits*, which is a system of the passive magnetic tangible designs that enables 3D tangible interactions in the near-surface space of portable displays. When a thin magnetic sensor grid is attached to the back of the display, the 3D position and partial 3D orientation of the *GaussBits* can be resolved by the proposed bi-polar magnetic field tracking technique. This portable platform can therefore enrich tangible interactions by extending the design space to the near-surface space. Since non-ferrous materials, such as the user's hand, do not occlude the magnetic field, interaction designers can freely incorporate a magnetic unit into an appropriately shaped non-ferrous object to exploit the metaphors of the real-world tasks, and users can freely manipulate the *GaussBits* by hands or using other non-ferrous tools without causing interference. The presented example applications and the collected feedback from an explorative workshop revealed that this new approach is widely applicable.

Author Keywords

Near-Surface Tracking; Portable; Occlusion-Free; Magnetism; Tangible Interactions.

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ACM Classification Keywords

H.5.2 [Information Interfaces and Presentation (e.g. HCI)]: User Interfaces

INTRODUCTION

TUI (Tangible User Interface) has been proven effectively to allow users to control and comprehend digital information as it supports direct manipulation and the utilization of spatial knowledge [14]. Since various advanced technologies are making prevalent mobile devices become increasingly powerful, some portable TUI approaches have been developed to improve the user experience. Although TUIC [27], Clip-on Gadgets [28] and CapStones [4] can exploit the characteristics of a capacitive touchscreen to sense on-surface tangible objects, the interactions are confined to the 2D space because of the limitations of the available sensing technology.

Such on-surface approaches allow users only to perform 2D tangible interactions but not 3D interactions, such as grasping an object by performing in-air steering (Figure 1(b)) – not only because the platform does not support near-surface tracking, but also because a grasping hand normally partially or fully occludes the target object. Although some vision-based [10, 26, 1] and traditional magnetic approaches [19, 12] can track the near-surface interactions, the former methods may suffer from the occlusion problem and the latter ones involve excessively heavy components for portable usage.

As a magnetic tracking method for portable devices, GaussSense [18] uses a thin-form Hall-sensor grid to detect the characteristics of a magnetic stylus, such as its hover position. Incorporating with a touchscreen allows information about the tilt and ID of a stylus to be determined. However, the proposed sensing mechanism and the magnetic tangible object (stylus) are specifically designed for pen applications on the 2D canvas. Hence, GaussSense does not support several essential features of near-surface tangible interaction design such as 1) sensing the roll of the tangible (while hovering), 2) sensing the tilt of tangible while hovering, and 3) tracking multiple magnetic tangibles. These limitations raise challenges in the transfer of this platform for the tracking of tangibles in the near-surface space. These challenges motivate the development of *GaussBits* herein.

GaussBits: Magnetic Tangible Bits

A *GaussBit* is a tangible object that contained a magnetic unit inside. As in GaussSense [18], a thin Hall-sensor grid is used for tracking. The key difference is that both N(orth)- and S(outh)-polar fields can be tracked at the same time. Based on the bipolar magnetic field tracking technology, several designs of magnetic tangibles that provide magnetic fields with suitable properties for sensing are showcased. The specifically designed magnetic unit allows the 3D position and partial 3D orientation (tilt or roll) of the magnetic unit to be stably resolved on or above the display. Therefore, it enables detection on tablets and non-touch LCD displays. The new detection algorithm further allows multiple objects to be tracked at the same time.

Figure 1 shows one of the demo applications of *GaussBits*, called *GaussPilot*. A Hall-sensor grid is attached to the back of a portable display, allowing the 3D position and tilt of a *Tiltable GaussBit* inside the toy aircraft to be resolved. A user therefore can tilt and/or hover the toy aircraft above the display to perform the flight simulation.

The *GaussPilot* highlights several promising features of its enabling technology. Since the sensor can track the remote magnetic field, a user can easily grasp a *GaussBit* to interact with the mobile device's display in the near-surface space as well as on the screen. Additionally, since the magnetic field can easily penetrate through any non-ferrous material, such as the user's hand, interaction designers can incorporate a *GaussBit* into an appropriately shaped non-ferrous object to exploit metaphors from simulating the real-world tasks, and users can freely manipulate the *GaussBit* by hands or using other non-ferrous tools without interfering with the tracking. This work will demonstrate three other example applications, which are *GaussClock*, *GaussNavigator*, and *GaussCooker*.

We also conducted an explorative workshop to investigate the possible applications of our approach. The results reveal that the enabled design space is easily adoptable, has various applications, and supports more inspiring and interesting spatial operations to enrich the experience of users.

The rest of the paper is arranged as follows. First, related work is discussed. Then, the design of *GaussBits* is introduced and several example applications are presented to illustrate the enabled design space. Then, the underlying mechanism is detailed, including an evaluation and an examination of limitations, and the feedback of users, gathered from the designers workshop, is presented. Finally, conclusions are drawn and directions of future work suggested.

RELATED WORK

Our approach enables occlusion-free tangible interactions in the near-surface space of portable displays, so related work is organized into the following categories: *near-surface tangible interactions*, *tracking tangible interactions on portable platforms*, and *occlusion-free tracking*.

Near-surface Tangible Interactions

The tracking of tangible objects in the near-surface space above an interactive surface has primarily been performed using vision-based methods, such as the use of AR markers[1] [8], motion tracker[2] for pen interaction [3], or feature tracking methods for 3D puppetry-based storytelling [10]. Ullmer and Ishii developed metaDesk [22] by utilizing computer vision and magnetic methods for object tracking to explore the tangible interactions on a desktop surface through a map application. SecondLight [15] enables near-surface interactions based on a computer-controlled diffuser, which allows a rear-projector to project images on and through the interactive surface. Chan *et al.* [5] extended SecondLight to a multi-display scenario on an interactive surface that embeds invisible markers using an IR (infra-red) rear-projector. ZeroN [17] further developed 3D tangible interactions by allowing an object to remain in mid-air using the magnetic levitation. Nevertheless, the vision-based methods typically suffer from the occlusion problem, and although magnetic motion-tracking methods such as Polhemus[3] are occlusion-free, the proposed settings makes them difficult to be integrated with mobile devices and difficult to be portable.

Tracking Tangible Interactions on Portable Platforms

Recently, the primary sensing technology on portable multitouch devices has been based on the capacitive sensing method. Before this technology became widely available, DiamondTouch [6] and SmartSkin [20] have demonstrated the tracking of conductive objects (such as tangible objects and fingers) on a capacitive sensing platform. Recent research has begun to develop tangible interactions on capacitive touchscreens [16]. Clip-on Gadgets [28] map user inputs to the rich-haptic gadgets' inputs at the touch points on the edges of mobile touchscreens. TUIC [27] presented capacitance tag designs in the space domain (such as passive 2D patterns) and time domain (such as active 1D frequency patterns) separately. Based on the concept of passing-down markers [2], CapStones [4] enables the stacking of widgets on mobile capacitive touchscreens. Owing to the limitations of the capacitive sensing technology, the tangible interactions are confined to 2D displays.

With respect to vision-based approaches, playAnywhere [26] is a portable camera-projector system that turns any surface into an interactive surface where tangible tracking is supported. ThinSight [11] turns a tablet's LCD screen into an

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[1] http://www.hitl.washington.edu/artoolkit/

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

[3] http://www.wacom.com/

interactive surface by inserting in-cell IR camera arrays at the rear of the LCD. Portico [1] tracks objects on the screen and the surrounding surface using two cameras that are positioned above the display. Though those vision-based approaches provide portable solutions and allow the interaction of tangible objects in the near-surface space above the display, they still suffer from the occlusion problem because of the limitations of the vision-based technology.

Occlusion-Free Tracking

Direct or low-frequency magnetic fields can pass through the body, making them suitable for use in occlusion-free tracking. Polhemus presented a high-resolution 6-DOF (Degree-Of-Freedom) tracking method using an electromagnetic field, but its sensing mechanism depends on an external emitter that makes it difficult to integrate into mobile devices. Passive resonant tags [19] can cause the resonance of the sensing electromagnetic coil array to provide ID, single axis position, and orientation information. A ferromagnetic input device [12] deploys an array of coils which allows to sense free-form ferromagnetic objects. However, both of these solutions are typically unsuited to portable use.

With respect to portability, magnetometers are used in many mobile devices and can track the 3D position of a passive magnet within a radial detection range [9], but the orientation of the magnetic field cannot be resolved. Although an electromagnetic resonance (EMR)[4] sensor can be integrated into a mobile touchscreen to detect the hover and tilt of a passive stylus, it can not resolve roll. SmartTable [21] utilizes a grid of Hall-effect switches to sense the information about the location and orientation of a 2D magnetic pattern on the surface, but it can sense only in 2D. GaussSense [18] use an analog Hall-sensor grid to detect hover and the tilt of a magnetic stylus on touchscreens. However, it's uni-polar magnetic fields tracking technique cannot recognize the roll of the stylus, or the tilt of a stylus while it is hovering, because the detection is associated with touchscreen input. The method also cannot track multiple magnetic styli at the same time. Hence, the feasibility of its extension to tangible interactions in 3D is unclear.

DESIGNING GAUSSBITS

A *GaussBit* is a basic design element for use with a magnetic field tracking technique. Based on the properties of a magnetic dipole field, which is symmetrically and uniformly distributed, the *GaussBits* can provide their 3D position information, and partial 3D orientation information through.

The basic operations that can be performed with the *GaussBits* are 3D translation, tilt, roll, and flip. The 3D translation of a *GaussBit* can be easily resolved by analyzing the distribution and the maximum strength of the sensed magnetic field, as has been discussed previously [18]. The present work focuses on designing *GaussBits* to enable the resolution of their roll and tilt. Neodymium magnets are used in prototype *GaussBits*. A bi-polar magnetic-field tracking sensor grid as shown in Figure 1(a), is used here to visualize the N- and S-polar magnetic field intensity maps of the *GaussBits* in red and blue, respectively. The IMPLEMENTATION section will provide details of the hardware and sensing mechanism.

Types of GaussBits

GaussBits designs are of two types: *Tiltable GaussBits* and *Rollable GaussBits*.

Tiltable GaussBits

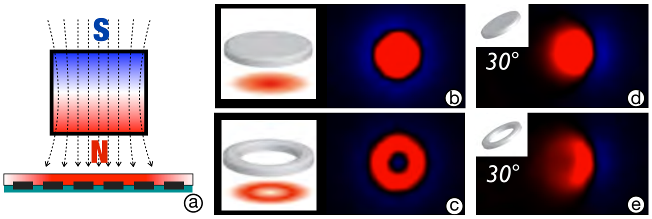

Figure 2. (a) Principle of *Tiltable GaussBits*, which can be made by using (b) cylindrical or a (c) ring magnets. Based on the magnetic field images shown in (d) and (e), tilt information can be extracted from the intensity map of the dipole fields.

To resolve the tilt of a *GaussBit*'s tilt information to be easily resolved in any direction without ambiguity, a cylindrical-symmetric 3D magnetic field between its two ends is required (Figure 2(a)). Therefore, the use of an axially magnetized cylindrical magnet, as shown in Figure 2(b) is suggested. If see-through capability is required, as in a magnifying glass application, an axially magnetized ring magnet as shown in Figure 2(c) can be also used. Figure 2(d)(e) show the magnetic field intensity map of the sample magnets. When the magnet is tilted, one side of it is higher than the other side, so the difference between the magnetic field intensities of the two sides provided tilt information. The flip operation can also be recognized from the change in polarity.

The tilt of a *Tiltable GaussBit* is estimated from the sensed shape of magnetic field. Accordingly, using magnets with larger radii provides more information and therefore a more precise estimate of tracking. With respect to limitations, however, the roll angle cannot be determined, because the cylindrically symmetric magnetic field is invariant under rotation.

Rollable GaussBits

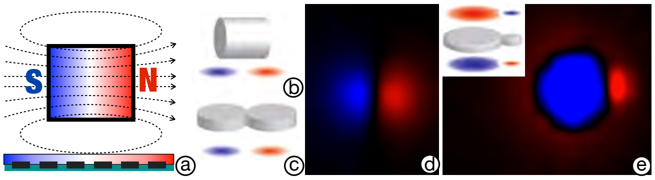

Figure 3. (a) Principle of *Rollable GaussBits*, which can be made from (b) a single magnet or (c) a couple of magnets. As show in (d) the image of the magnetic field, roll information can be determined from the relative position of the dipole. (e) Example of a flippable *Rollable GaussBit*.

The simplest way to resolve the roll angle of a *GaussBit* accurately is to lay down a *Tiltable GaussBit* to let the direction of the magnetization parallel to the surface as shown in Figure 3(b), or to attach another opposite-polar magnet by the *Tiltable GaussBit* as shown in Figure 3(c). The magnetic field intensity map then becomes as shown in Figure 3(a), and the N-part and S-part of the magnetic field can be easily observed. The direction of rotation can therefore be resolved

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[4] http://www.wacom.com/

from the relative positions of these two parts without ambiguity (Figure 3(d)).

Because the magnetic field of a *Rollable GaussBit* is not cylindrically symmetric, tilt is ambiguous to determine at some angles. However, the flip operation still can be detected by keeping one polar field stronger than the other, as shown in Figure 3(e), so that the sensor can “see” which side is facing down by recognizing the polarity of the strongest part of field. The asymmetry designs introduced herein support carrying identification of *GaussBits*, which will be discussed later.

Summary

Currently, a *GaussBit* cannot be designed to support the full set of 6-DOF operations without ambiguity, because both types of *GaussBits* exploit either symmetry or asymmetry of a magnetic field – and these properties are mutually exclusive. However, both types of *GaussBits* support interaction in the near-surface space above a portable display, rather than only on the display. Although the interaction space is limited to the sensing range, which is usually less than 5cm, it suffices for users to interact with the content on the display in various scenarios. In the next section, several example applications will be presented to demonstrate the capabilities and the tangible interaction design space enabled by *GaussBits*.

EXAMPLE APPLICATIONS

Four example applications are presented to demonstrate how *GaussBits* can support tangible interactions on or above portable displays. In all applications, *GaussBits* are tracked using a Hall-sensor grid (Figure 1(a)), which is attached behind the portable displays, as shown in Figure 4(a)(b).

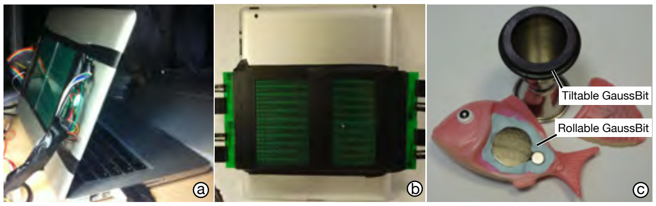

Figure 4. Hardware used in applications. Hall-sensor grid is attached behind (a) an unmodified laptop display and (b) an unmodified capacitive touchscreen. (c) *GaussBits* used in one application, *GaussCooker*.

GaussClock: Rolling on 3D

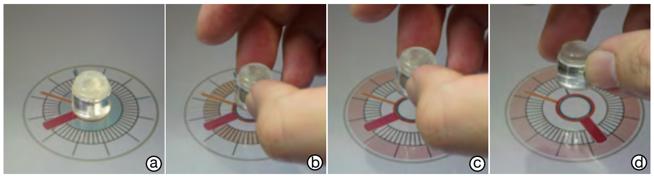

Figure 5. A simple clock widget, *GaussClock*, is presented here to demonstrated the use of a *Rollable GaussBit* as a multi-level dial. (a) The *GaussClock* on the surface of display indicates that the second hand is adjustable. (b) Lift the *GaussClock* in the bottom of the near-surface space to set the minute hand. (c) Lift the *GaussClock* higher to set the hour hand. (d) Rotate the *GaussClock* in the air to adjust the hour hand.

GaussBits can be manipulated above the display. A multi-level dial, *GaussClock* (Figure 5), is demonstrated. It is a widget for adjust ing a clock. A laid 10mm-height×4mm-radius cylindrical magnet in an acrylic case is used as a *Rollable GaussBit*, and a 5mm-thick LCD, mounted a Hall-sensor grid in the back is used as the display, as shown in Figure 4(a).

When the *GaussClock* is placed on the surface, the second hand of the clock is displayed to be adjustable. When the *GaussClock* is lifted to the lower or higher near-surface space, the minute or hour hand of the clock is shown to be adjustable, respectively. A user can rotate the *GaussClock* to adjust the selected hand.

Since the sensing becomes less precise as the height of hovering increases [18], this property is mapped to the operands. The *GaussClock* on the surface can be sensed precisely, and the supporting surface also serves as a firm reference for the precise control. Hence, a user can perform precise adjustments, such as of the seconds. Coarse-scale control such as adjusting the hours are better performed in the air.

GaussNavigator: Hover, Tilt, and Flip

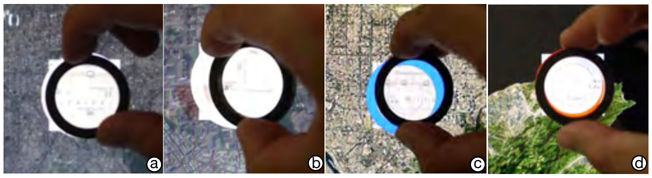

Figure 6. A map navigator, *GaussNavigator*, is presented here to demonstrated how a *Tiltable GaussBit* can extend the dimension of control (a) When *GaussNavigator* is placed on the surface, information of interest is displayed inside the ring and context information is displayed outside it. (b) Tilt the *GaussNavigator* to navigate around the map. (c) Lift the *GaussNavigator* to zoom-out the map at the corresponding hover position. (d) Flip the *GaussNavigator* to switch function to zoom-in.

A tangible map navigator, *GaussNavigator* (Figure 6), is presented here to demonstrate the extension of the control scope in tangible map navigation. A 3mm-height×19mm-outer-radius×15mm-inner-radius ring magnet is used as a *Tiltable GaussBit*, because this application requires see-through capability. The hardware configurations for sensing and display are the same as those of *GaussClock*.

When a *GaussNavigator* is placed on the map, detail information of the area of interest such as the street names are shown inside the ring, and the contextual information such as the satellite view are shown outside it. The user can move it freely to see around the areas of interest. When the user wants to visit the area outside the current viewport, he or she can tilt the *GaussNavigator* to scroll the map. The speed and direction of scrolling depends on how the *GaussNavigator* is tilted. To zoom-out the map, the user can lift the *GaussNavigator* from the surface, then the map is zoomed-out at the hovering position. In contrast, if the user wants to zoom-in the map, he or she can rapidly switch between modes by flipping the *GaussNavigator* in the near-surface space.

The hover, tilt, and flip operations provide intuitive mode switching during navigation of the map. Users can intuitively use *GaussNavigator* based on existing spatial knowledge.

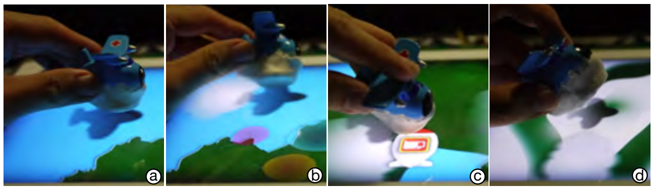

Figure 7. A tangible pilot simulator, *GaussPilot*, is presented here to demonstrate the benefits of an occlusion-free method in providing favorable form factors and real-world metaphors. (a) A user can grasp the *GaussPilot* by pinching to control it above the display. The on-screen virtual shadow provides information on tracking. (b) Avoid the obstacles by tilting the *GaussPilot*. (c) Land the *GaussPilot* on the screen to pick up the bonus. (d) Lift the nose of the *GaussPilot* to climb.

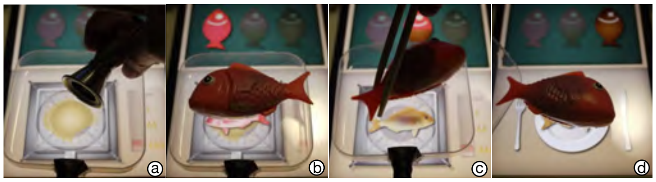

Figure 8. A fish-frying simulation, *GaussCooker*, is presented here to show how a user can manipulate *GaussBits* using other non-ferrous instruments, based on magnetic penetration. (a) Tilt the measuring cup to pour some soybean oil into the pan before frying the fish. The pan is made of 2mm-thick plastic. (b) Place the fish on the plastic pan. (c) Flip the fish using the wooden chopsticks. (d) Hold and shake the pan to fry the fish, and then pour the fried fish onto the dish (display).

GaussPilot: Occlusion-Free Control

A tangible flight simulator, *GaussPilot* (Figure 7), is shown here to demonstrate the advantages of the occlusion-free property. Since magnetic field tracking is unaffected by non-ferrous material, a *Tiltable GaussBit* that is made of a 3mm-height×15mm-radius cylindrical magnet is stuffed into the plastic toy aircraft, which the user can grasp the object in his or her hand. The display is an 8.7mm-thick iPad2[5] on the back of which is attached a Hall-sensor grid (Figure 4(b)).

Since the physical object is shaped properly, users can control the *GaussPilot* based on their knowledge of piloting a toy aircraft. A users can control the *GaussPilot* by pinching the toy aircraft above the display. A virtual shadow visualizes tilt information and hover position to indicate to the user whether the aircraft is off-track. To avoid obstacles, the user intuitively tilts the *GaussPilot* intuitively. To pick up the virtual bonuses, the user can land the *GaussPilot* on the screen temporarily at the correct position. A user can also raise or lower the nose of the *GaussPilot* to climb or dive, respectively.

This application demonstrates that the occlusion-free sensing technology overcomes the limitations of physical form design, allowing designers freely to customize objects to help users better perceive the available set of operations [7]. Moreover, since an object can be made of non-conductive materials, the original capacitive touch sensing is not interfered with. Hence, designers can freely add features such as touch+tangible interactions [25] or apply other ID techniques [27] through the as-yet unused touch input. Finally, the application scope has been extended from 2D to 3D.

GaussCooker: Penetrating non-GaussBits

In daily life, people interact with physical objects by using not only their hands but also other tools. Occlusion-free sensing can bring this experiences into tangible interaction design. A cooking game, *GaussCooker* (Figure 8), uses two *GaussBits* in a cooking simulation. They are a toy fish and a measuring cup (Figure 4(c)). The toy fish is embedded with a flippable *Rollable GaussBit*, which is made of a combination of a 6mm-height×12.5mm-radius and a 10mm-height×4mm-radius cylindrical magnets. The measuring cup contains a *Tiltable GaussBit*, which is made of a 3mm-height×15mm-outer-radius×12mm-inner-radius ring magnet. A non-*GaussBit*, a plastic frying pan, is used to hold the fish and the soybean oil that is poured from the measuring cup. The frying pan is made of 2mm-thick translucent plastic to allow users to see the information that is displayed on the screen. The hardware setup is similar to that in *GaussPilot*.

To fry a fish in the game, a user firstly tilts the measuring cup above the frying pan to pour out the soybean oil. Then, he or she can put the fish into the frying pan, which is distinguished from from the measuring cup by the sensing of its different magnetic field. Then, the user can shake the frying pan to fry the fish, which action is determined by tracking the motion of the fish. The user can flip the fish using the wooden chopsticks, which are non-*GaussBits* as well. The user can continue to fry the fish, and then slide the fried fish out of the pan onto the dish. This action is recognized from the increase in the sensed intensity of magnetic field.

Owing to the penetration of magnetic fields into non-ferrous objects, *GaussBits* can be manipulated on other non-ferrous objects, and still can be detected properly. Hence, designers can combine *GaussBits* with other non-*GaussBit* objects to simulate tasks in more realistic and intuitive ways.

IMPLEMENTATION

In this section, the hardware and the sensing algorithm are detailed first, then the limitations are evaluated and discussed.

Hardware for Magnetic Field Tracking

The magnetic sensor grid that is shown in Figure 1(a) consists of 32 × 24 = 768 Winson[6] WSH138 Hall sensors, with an area in 160 (W) × 120 (H) mm^2. Each sensor element detects both N- and S-polar magnetic field intensities, in a range from 0 to 200 Gauss on a 256-point scale. All sensor data are multiplexed and transferred to a PC through a Teensy[7] 2.0 micro-controller via a USB connection. The captured bi-polar magnetic field data are 16x up-sampled using the bi-cubic interpolation method (or the bi-linear interpolation method for the sensors at the boundaries) to a 496 × 368 bitmap with the sampling rate consistently above 30fps, and map the N- and S-polar magnetic field at each sample points is mapped to a red or blue color intensity of the corresponding pixel on the bitmap, respectively.

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[5] http://www.apple.com/ipad/

[6] http://www.winson.com.tw/

[7] http://www.pjrc.com/teensy/

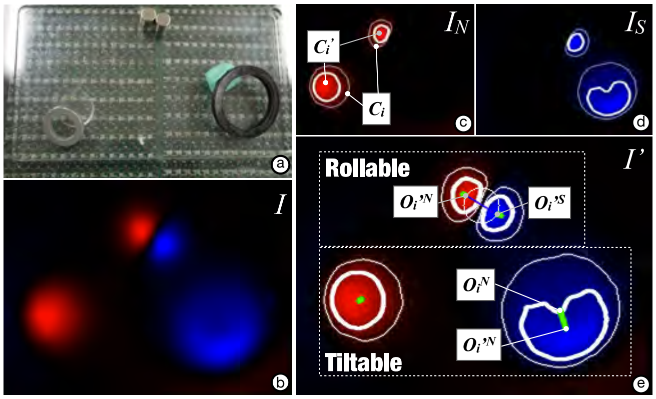


Figure 9. Signal processing procedures. (a) When magnets are placed on the sensor grid, the magnetic field image I can be obtained as shown in (b). Separate analyses of the (c) N-Field I_N and (d) S-Field I_S enables the connected components C_i and their feature C_i' to be extracted from both field images. (e) Combining the two images enables the sensing algorithm to resolve the position and orientation of *Rollable GaussBits* and *Tiltable GaussBits*.

Sensing Algorithm

The sensing algorithm is developed to track the location and orientation of *GaussBits* in the near-surface space by analyzing the obtained bi-polar magnetic field image I (Figure 9(b)).

Preprocessing

The raw sensing image I consists of N- and S-polar parts, which are I_N (Figure 9(c)) and I_S (Figure 9(d)), respectively. If the sensed intensity value is below a given noise threshold T_{noise}, then it will be treated noise data and will be removed. To analyze the position of *GaussBit*, all connected components C_i are extracted from both I_N and I_S. If the extracted C_i is too small or falls inside a larger one, then it is removed. The remaining C_i are fitted using a rotational bounding box. The centroid O_i of the bounding box, and maximum intensity value I_{max} of each C_i are then calculated. The O_i and the I_{max} can be used to resolve the 3D position *GaussBit*.

To obtain orientation information, the filtered C_i must be further processed. When I_{max} exceeds $T_{noise} + k$, where k is a constant, the feature C_i' of every C_i is extracted by imposing a higher theshold $T_{high} = I_{max} - k$. The rotational bounding box is again calculated for C_i' to obtain the centroid of the box O_i'. Analyzing each O_i' with the corresponding O_i and I_{max} in both I_N and I_S yields the orientation information.

Identifying and Sensing Types of GaussBit

The detected C_i and C_i' can be used to determine whether the *GaussBit* is a *Tiltable GaussBit* or a *Rollable GaussBit*. If a C_i' is detected within C_i, of which the polarity is the same as C_i', then this C_i'-C_i pair is regarded as a *Tiltable GaussBit*. On the contrary, if an N-pole C_i' is within a predefined threshold distance of an S-pole C_i', then this $C_i'^N$-$C_i'^S$ pair is identified as a *Rollable GaussBit* rather than two *Tiltable GaussBits*.

For a *Tiltable GaussBit*, the projected position onto the 2D plane is O_i, and I_{max} determines the hover height. The direction is given by the vector $\vec{v} = \overrightarrow{O_i - O_i'}$, and the angle of tilt can be determined from $||v||$.

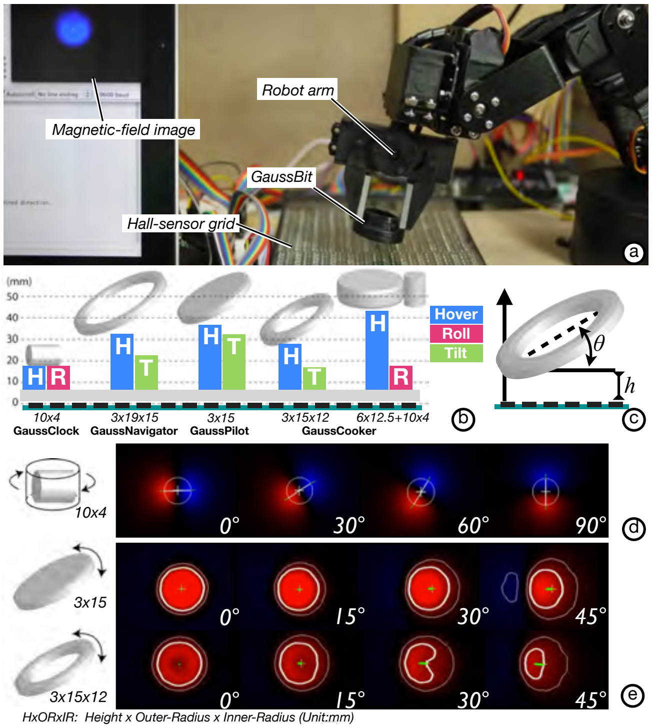


Figure 10. (a) Experimental apparatus. (b) Sensing distance of the sample *GaussBits*. Within this distance, the position of hovering and the directions of roll or tilt can be resolved. (c) Definition of sensing distance h and tilt angle θ. (d) Resulting magnetic field images of a *Rollable GaussBit* sample and (e) two sample *Tiltable GaussBits* at a hover height of 10mm at four roll and tilt angles.

For a *Rollable GaussBit*, the projected position onto the 2D plane is the midpoint of $O_i'^N$ and $O_i'^S$, and $Max(I^N_{max}, I^S_{max})$ determines the hover height. The direction of the roll is given by $\vec{v} = \overrightarrow{O_i'^S - O_i'^N}$. If the application involves only one *Rollable GaussBit* as in the *GaussClock* application shown, O_i^N and O_i^S can be used instead of $O_i'^N$ and $O_i'^S$ to increase the sensing distance.

Based on the proposed algorithm, the tilt or roll of the *GaussBits* can be correctly resolved, as shown in Figure 9(e).

Evaluation

An earlier study [18] revealed that the sensing performance becomes worse as the sensing distance is increased. Therefore, an in-lab measurement was made to determine the maximum sensing distance of the proposed algorithm. The five *GaussBits* that are demonstrated in the four applications, *GaussClock*, *GaussNavigator*, *GaussPilot*, and *GaussCooker*, are evaluated here.

Procedures

A calibrated robot arm, shown in Figure 10(a), which can perform lift, tilt, and roll operations, is used to measure stably the performance of each *GaussBit* in the air. The measurements started from a height of 5mm, which equals the thickness of the laptop LCD that was used in the application. In each trial, the hover height is increased by 1mm, and the tilt (0° ~ 45° pitch) or roll (0° ~ 360°) function is tested, according to the type of *GaussBits*. When the operation cannot be resolved, the test is terminated and the height is recorded as the maximum sensing distance of the corresponding function. The T_{noise} was set to 30 Gauss to filter out the unwanted noises, and the k was set to 40 Gauss to extract features. Figure 10(b) shows the specifications of the five tested *GaussBits*.

Results and Discussion

The sensing distances of the tested *GaussBits* range from 17mm to 44mm (Figure 10(b)), as the magnets that are embedded inside the *GaussBits* varied among the applications. Within the sensing range, the direction of tilt or roll is correctly resolved as shown in Figure 10(d)(e). Using stronger magnets and/or using more sensitive Hall sensors for sensing can improve the detection range.

The green lines in Figure 10(e) represent the tilt angles. The length of the green line is proportional to the actual tilt angles of the *Tiltable GaussBits*. However, different *Tiltable GaussBits* provide differently shaped magnetic fields, the sensed tilt angles vary. Proper calibration is therefore required before tilt angle can be enabled as a feature to be tracked. Another limitation is that when the user tilts the magnet by more than 45°, the system may misinterpret a *Tiltable GaussBit* as a *Rollable GaussBit* if magnet is as thin as that used herein. We expect more sophisticated learning and classification techniques to eliminate this ambiguity in future. Generally, all of the tested *GaussBits* have a large enough sensing distance to support the intended interactions, and the sensing algorithm initially proves the concept.

CHALLENGES OF TRACKING MULTIPLE GAUSSBITS

One of the primary advantages of the tangible user interface is the space-multiplexed input [13]. To realize space-multiplexed input, we have implemented the multiple-tangible tracking algorithm. However, two major challenges, *interference* and *identification*, are needed to be solved. In this section, we discuss these challenges and propose the possible solutions.

Interference

Nearby magnetic fields can easily interfere with a *GaussBit*, making the management of multiple magnetic tangibles on the display difficult. Our algorithm already filters out any unwanted magnetic field that may interfere with tracking. However, the shape of the magnetic field may be distorted by a very nearby field, and the fields may merge. For examples, as shown in Figure 11, when two 3mm-height×15mm-outer-radius ring magnets are placed on a 5mm-thick laptop LCD, to the back of which is attached the Hall-sensor grid, they have a minimal interference-free distance of 11mm when they are in the same polarity. At shorter distances, unexpected results are obtained. Under the condition of opposite polarities, each of the positions of the magnets can be resolved even when they are attracted to each other, but the strong attractive force may impede user interactions.

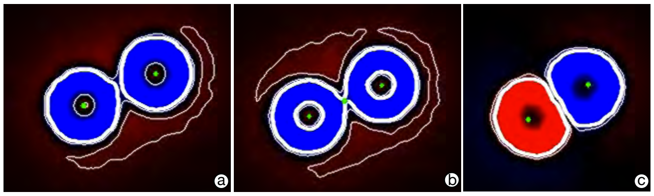


Figure 11. Magnetic field between multiple *GaussBits* may interference with sensing. (a) Under the same-polarity condition, the *GaussBits* are correctly detected when they are sufficiently far from each other (1.5cm), but (b) the detection may fail when two *GaussBits* are too close (1cm) to each other. (c) When the polarities of two*GaussBits* are opposite each other, each of them can be resolved even when they are attracted to each other, but the strong attractive force may inhibit user interactions.

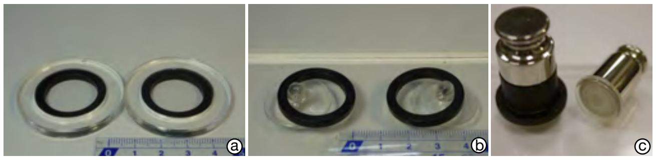


Figure 12. Possible ways to eliminate interference. (a) Firm cases or (b) physical constraints can prevent two magnets from being too close to each other. (c) Adding a weight (left one) and a friction pad (right one) to the *GaussBits* can increase the surface friction to reduce interference.

To solve the above problem, a straightforward solution is to impose physical constraints [23], such as a firm casing to prevent the magnets from moving too close to each other, as shown in Figure 12(a)(b). Increasing the friction of the magnetic objects against the surface helps to handle attractive or repulsive magnetic forces. Friction can be increased by adding weight to the magnetic objects, or by attaching materials that have a high coefficient of friction, such as a silicon pad, to the bottoms of the objects (Figure 12(c)).

Identification

Since the shape of the magnetic field is similar with the shape of the magnet, the shape of the magnets can be designed for carrying ID information. Complement with other ID techniques can also increase the number of usable IDs.

Using Shape of Magnetic Field to Identify GaussBits

Ring-shaped magnets are used to describe how the shapes of magnetic fields can be used to identify *GaussBits*.

A straightforward method for identification is to carve a gap in the side of a ring-shaped magnet, as shown in Figure 13(a)(b). The position of the gap yields the orientation of the magnet (Figure 13(c)). The length of the gap can be used to identify the magnet (Figure 13(d)). This ID method retains the single-piece property of *GaussBits*, but the ID design space is limited to the size and shape of magnet.

Another method for identification is to attach small cylindrical magnets to the side of a ring-shape magnet as shown in Figure 13(e). Since the magnetization of the attached cylinders opposes that of the ring as shown in Figure 13(f), the cylinders can be easily discriminated from the ring. Accordingly, if the cylindrical magnets are attached asymmetrically, then the combination of magnets can not only yield the orientation of roll, but also identify the object, as shown in Figure 13(g). This ID method provides ease of prototyping and facilitate identification. Nevertheless, combining multiple magnets enlarges the *GaussBits* and may require casing to fix the magnets around the ring.

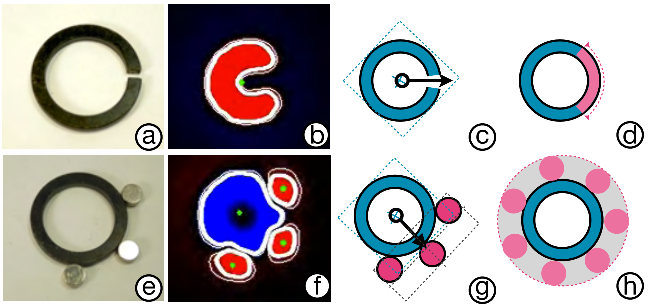


Figure 13. Two methods identifying rollable magnets while determining the orientation of roll. (a) Carving a gap in the side of a ring magnet yields the magnetic field that is shown in (b). (c) The image of the magnetic field shows that the gap can be clearly used to provide the orientation. (d) The pink area represents the ID design space. (e) Attaching one or many cylindrical magnets to the side of a ring magnet yields the magnetic field image in (f). (g) The orientation can be resolved and (h) the pink area represents the ID design space.

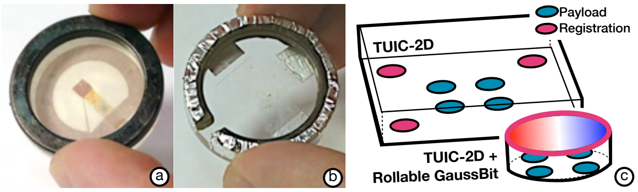
Scalability of shape as ID: Since multiple magnets are attached to each others in the identification method, scalability should be considered because of interference. For the ID design that is shown in Figure 13(e), a 3mm-height×4mm-radius cylindrical magnets where attached around the central ring magnet as a payload, which had a minimal interference-free distance of 9mm. Hence, the 3mm-height×19mm-outer-radius magnet had a 7-bit ID space, as shown in Figure 13(h), in which the asymmetric patterns can be used to provide roll information as well.

When a user lifts or tilts the *GaussBits* from the surface, the image of the magnetic field becomes blurry, potentially shrinking the ID design space. The ID design in Figure 13(e) was tested on a 5mm-thick LCD panel. Its ID was detected robustly when the *GaussBits* hovered 9mm above the display or when they were tilted with a pitch or yaw of ±15 degrees on the display.

Generally, although the capability of using shape for identification is limited and the number of IDs is proportional to the resolution of the sensing platform, this method is still usable for applications that require only a few tangibles.

Combination with Other ID Techniques

If many IDs are required, then *GaussBits* can be combined with other passive ID techniques, such as the use of an NFC tag, by attaching the passive NFC tag to the bottom of a *GaussBit*, as shown in Figure 14(a), or the use of capacitance tags, by deploying a conductive pattern to the bottom of a *GaussBit*, as shown in Figure 14(b). Combining both techniques provides the advantages of both. The comparison table (Figure 14(d)) clearly illustrates the benefits of combining *GaussBit* with NFC or TUIC-2D [27] tags. Especially, when combined with the capacitive TUIC-2D passive tag, a *Rollable GaussBit* can effectively reduces the required size of TUIC-2D tag because its magnetic field can provide registration information, such as the orientation and position of the tag, as shown in Figure 14(c). Therefore, the smaller tag is better suited smaller portable capacitive multitouch displays, such as in smartphones.



Available Information/ Type of Tag	ID	Location		Orientation		Note
		2D (x,y)	Height (z)	Rotation (Roll)	Tilt (Pitch & Yaw)	
NFC Tag	v					
TUIC-2D	v	v		v		
Tiltable GaussBit	Δ	v	v		v	
Rollable GaussBit	Δ	v	v	v	Δ	
TUIC-2D + Tiltable	v	v	v		v	
TUIC-2D + Rollable	v	v	v	v	Δ	*
NFC + Tiltable	v	v	v		v	
NFC + Rollable	v	v	v	v	Δ	

Δ: Partial *Can be made smaller than original. ⓓ

Figure 14. ***GaussBits*** **complement other identification techniques to increase the number of ID numbers.** ***GaussBits*** **can be enhanced by using an (a) NFC tag, or (b) capacitive-based tag. (c) When combined with the TUIC's technique,** ***GaussBits*** **can effectively reduces the size that is required by TUIC. (d) The table shows the benefits of combining** ***Tiltable GaussBits*** **or** ***Rollable GaussBits*** **with other ID techniques.**

EXPLORATIVE WORKSHOP

To understand how this enabling design space can be applied to design TUI applications for portable displays, eight designers (3 female and 5 male) were recruited from a design school to participate in an explorative workshop. All of them were senior graduate students, and had more than a year of experience of participating in brainstorming workshops.

Procedures

First, relevant fundamental knowledge, including the available interaction set and limitations of this technology, is presented. Then, the four applications herein were presented to the designers to allow them to experience the technology (Figure 15(a)). Then, paper clay, various kinds of magnet, stacks of 3M post-it memos, and white paper were distributed to the designers. With the paper clay in hand, designers could make tangible prototypes while brainstorming, and share their thoughts through the think-aloud protocol. To ensure the quality of the discussion, participants were split into two equally sized groups. Each group engaged in an explorative workshop that lasted for two hours, and all activities were video-recorded.

Results and Discussion

During the two-hour workshop, various ideas were generated and discussed. Those ideas can be roughly divided into four categories, which were *real-world simulation*, *entertainment*, *toolkits*, and *display as a tool*.

Real-world simulation: By shaping the tangibles into the desired form, designers can easily simulate the tasks from the real world. For example, one designer thought about attaching a handle to the ring-shaped *GaussBit* to simulate a magnifying glass, to assist with interior design tasks, or to help the tourists navigate a city map. Other ideas, such as gardening with physical tools (Figure 15(b)), or sculpting with a knife,

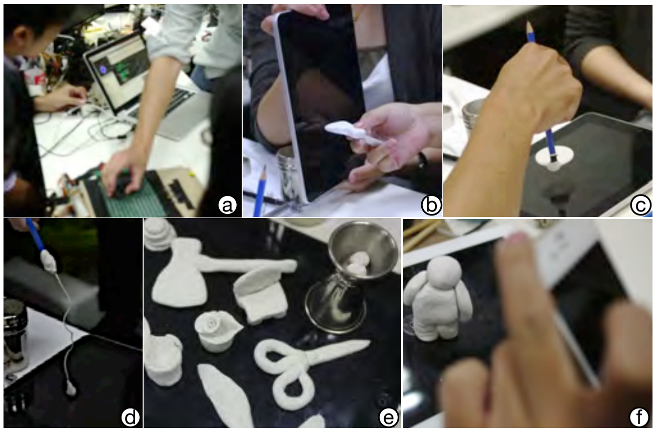


Figure 15. Explorative workshop. (a) A designer is experiencing the *GaussBits* technology, and then making prototype tangibles using paper clay while in brainstorming. Some tasks from the real-world simulation are proposed like (b) wielding an axe to chop a tree; (c) using a metal detector to hunt for treasure, and (d) fishing with a bait made of a *GaussBit*. (e) One designer made a toolkit for virtual gardening. (f) One designer thought that the smartphone could be used as a special lens to augment the related information of the *GaussBit*, and that as the tilt angle was varied, the provided information might also vary.

were mentioned and discussed very early. The designers also felt that they could easily use their common knowledge to perform these tasks.

Entertainment: Since most downloaded applications on mobile devices are games, some designers thought that tangible objects could be designed to enhance the experience of gaming. A range of games were considered. They included holding a toy car for racing, hunting for treasure using a metal detector (Figure 15(c)), and fishing with a rod with a magnet as the bait (Figure 15(d)). Games with educational purposes, such as teaching color mixing using different color bottles, teaching chemical reactions by treating each tangible as a particular chemical solutions, or teaching invisible magnetic interactions by displaying magnetic flux were proposed. Designers felt that holding a physical controller make game playing more engaging.

Toolkits: Rather than designing a general-purpose tangible, designers thought that a series of specific-designed tangibles as toolkits would be more useful for some applications. For example, a doctor requires different medical instruments to cure a virtual patient, and a gardener requires various tools to planting virtual flowers or watering virtual plants (Figure 15(e)). The designers thought that such tools could be placed on or around the device, and that users could choose the required one and use it to interact with the display.

Display as a tool: The designers tried to utilize their handheld devices to interact with the *GaussBits*. One designer said that rather than moving a *GaussBit* above a display, users could fix a larger *GaussBit* on the table and move a mobile display to explore around it; then, the display would augment the related information about the object from the distance and angle between the device and the *GaussBit* (Figure 15(f)). They also thought that the *GaussBits* could support remote collaboration with a shared working space. For example, two people could work together with their own tablet computers, manipulating their own physical tools to perform a collaborative task on both displays. The interactions between the remote collaborative workspaces are synchronized through the wireless network connection.

The proposed wide range of applications demonstrates that *GaussBits* are easily usable, and would be applied in interesting ways by interaction designers when magnetic-field tracking becomes available as a feature in commodity hardware.

FUTURE WORK

This work is limited in several ways, which we intended to overcome in future work. First, the range of application is limited by the resolution and form factors of the hardware prototype. Better manufacturing of the sensor hardware can increase the sensing resolution, and different form factors can be used with various portable displays, such as flexible OLEDs. Second, although the detection with the proof-of-concept sensing algorithm, which is designed based on experimental data, is effective, exploiting the essence of magnetism is a promising way to further improve the performance of this technology. Finally, the current hardware prototype is not easy for designers and developers to use. We believe that developing an easily adoptable prototyping toolkit will lead to more interesting applications and provide a platform for further research into near-surface tangible interaction design.

CONCLUSION

In this work, magnetism is utilized to enable tangible interactions in the near-surface space of the off-the-shelf portable displays. Two types of *GaussBits*, *Tiltable GaussBits* and *Rollable GaussBits*, are introduced. They can be robustly tracked in the near-surface space by the developed sensing algorithm and the prototype Hall-sensor grid. Since the sensing mechanism is occlusion-free, non-ferrous materials can be used to shape the *GaussBits*. How the enabling technology can enrich the mobile interaction experience is demonstrated using four applications, which are *GaussClock*, *GaussNavigator*, *GaussPilot* and *GaussCooker*. These applications show how can leverage their spatial knowledge using easily understood metaphors to carry out interactions. The explorative workshop also revealed that the interaction design space that was enabled by the proposed approach is easily applicable, and it suggested many promising directions for future developments.

GaussBits advance tangible interactions on portable displays by providing occlusion-free 3D interactions in the near-surface space. We hope that the broader CHI community can apply this technique to develop more novel designs to exploit the quiescent meanings [24] of tangible interactions.

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