GaussStones: Shielded Magnetic Tangibles for Multi-Token Interactions on Portable Displays

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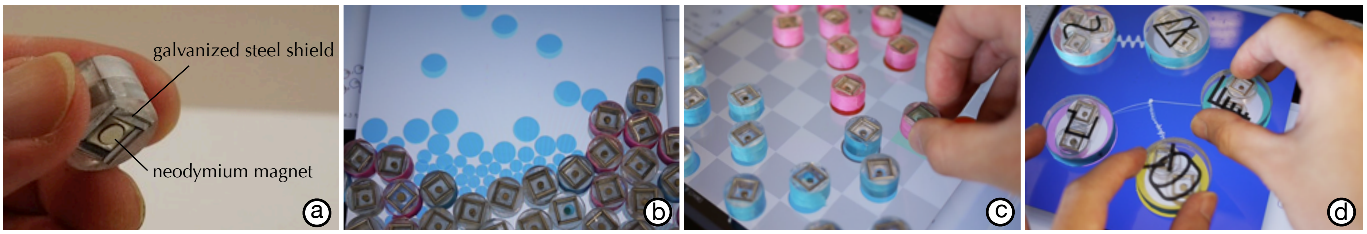

Figure 1. (a) GaussStones are magnetic tangibles with magnetic shielding that eliminates interference between magnetic tangibles and enables various multi-token applications on portable displays, including (b) sculpting and simulation, (c) board gaming, and (d) live music performance.

ABSTRACT
This work presents *GaussStones*, a system of shielded magnetic tangibles design for supporting multi-token interactions on portable displays. Unlike prior works in sensing magnetic tangibles on portable displays, the proposed tangible design applies magnetic shielding by using an inexpensive galvanized steel case, which eliminates interference between magnetic tangibles. An analog Hall-sensor grid can recognize the identity of each shielded magnetic unit since each unit generates a magnetic field with a specific intensity distribution and/or polarization. Combining multiple units as a knob further allows for resolving additional identities and their orientations. Enabling these features improves support for applications involving multiple tokens. Thus, using prevalent portable displays provides generic platforms for tangible interaction design.

Author Keywords
Magnetism; Tangible Interactions; Portable Display; GaussSense; Analog Hall-Sensor Grid

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

INTRODUCTION
Prevalent portable displays provide tangible interaction experiences for users by tracking physical objects. In addition to traditional vision- and capacitive-based object tracking methods, researchers have begun exploiting magnetic object tracking in tangible interaction designs for several reasons. First, since magnetics can provide signals for 3D tracking without batteries and micro-controllers, magnetic tracking sensors are easily maintained and constantly available. Moreover, magnetic tracking sensors such as magnetometers [8] and analog Hall sensor grids [15] are highly portable and easily retrofitted to existing devices without hardware modifications. Object tracking mechanisms can track multiple objects on, above, and around devices with high robustness and high responsiveness [8, 14]. These promising features enhance the potential applications of tangibles in interactive surfaces.

However, since nearby magnetics naturally repel or attract each other, a general limitation of magnetic tangibles is the shortage of supporting applications that involve multiple tokens. To compensate, additional mechanisms may be needed to fix them to the surface, e.g., by using glue [8], adding weight [14], attaching friction pad to the bottom of token [14], or attracting the magnetic token to a ferro-surface [12]. Adding these mechanism on the tokens not only reduces freedom of control, but also constrains the tangible interaction design.

GaussStones: Shielded Magnetic Tangibles
This work presents GaussStones (Figure 1), a system of shielded magnetic tangibles, which solves the above problems in analog Hall-sensor grid tracking and in portable display object tracking. Unlike prior works [14], each GaussStone is shielded with a case made of inexpensive but highly permeable metals (e.g., galvanized steel), which isolates its magnetic field and prevents interference with others on the surface. Each GaussStone provides a sufficiently strong magnetic field as a signal source that the sensor grid can use to identify its position and orientation. Each GaussStone can be

differentiated by its magnetic polarity and/or intensity distributions. Therefore, the system can support multi-token applications in portable displays, including sculpting and simulation, board gaming, and live music performance.

The proposed shielded magnetic tangible design uses numerous small but easily identifiable tokens in portable displays to facilitate space-multiplexed input. Moreover, the small token size allows users to perform embodied gestures such as gathering the particles (tokens) on the portable displays in haptic-rich ways that can be detected precisely by the system. The tokens have the same benefits of magnetic tangibles, i.e., they can be robustly sensed without contact, even when occluded or in darkness. Thus, they can provide continuous and satisfiable user experiences.

The rest of the paper is organized as follows. First, related work is discussed. Magnetic shielding principles are then explained, and the design space of this technique is explored. The proposed design for magnetic tangibles and its applications are then introduced. Finally, possible generalizations and limitations of this technique are discussed.

RELATED WORK

Tabletop tangible user interfaces enable simultaneous two-handed and multi-user by providing multiple tangibles in the interactive surface applications [9], such as board gaming [2], music editing [11], and particle-based simulations [18]. In these applications, users can rapidly access binding information and computational models by grasping and manipulating physical tokens [21], which provide immediate and realistic haptic feedback for users on the afforded 3D gestures.

Recent studies have attempted to apply advanced object tracking capability in prevalent portable platforms. The primary object tracking method uses a capacitive multitouch panel for object tracking [19, 5]. TUIC [24] presented capacitance tag designs for identifying different tangibles by passive 2D patterns or by active 1D frequency patterns. A method of disambiguating the capacitance tag and user finger touch was also proposed for each tag type. In Capstones [4], combinations of stacked tangibles can be identified by mapping the combinations to different 2D marker. The PUCs [22] further demonstrated the feasibility of detecting capacitive tangibles without touch. Transparency is achieved by applying indium tin oxide (ITO) coatings. These works demonstrated the successful use of capacitance tags for identifying multiple objects or individual objects. However, since most current portable platforms are mainly used for sensing finger touch and regard touch as a binary event, they cannot effectively discriminate touch and objects by] single touch point. Therefore, they have additional space requirements (passive 2D pattern) or power requirements (active frequency tag) [24] for disambiguating different tags and finger touches. These additional requirements hamper the multi-token interactions on small portable displays.

Methods other than capacitive tracking include SenseTable [17], which was implemented in a tangible workbench by using an electromagnetic resonance (EMR)[1] sensor. EMR sensor has recently been embedded mobile devices to detect a passive stylus[2]. The PICO [16] further uses LC-Tag tracking technologies to simplify puck designs for multi-token tracking. However, since most conventional portable displays do not support EMR- and LC-tag sensing, these systems are difficult to implement in portable displays. Since most of portable displays have a built-in magnetometer, Magnetic Appcessories [3] and MagGetz [8] used the magnetometer to identify and sense multiple magnetic widgets on and around the display. Although magnetometers are highly portable, widgets requires calibration before use, and the positions of tangibles must be fixed, which reduces the degree of freedom.

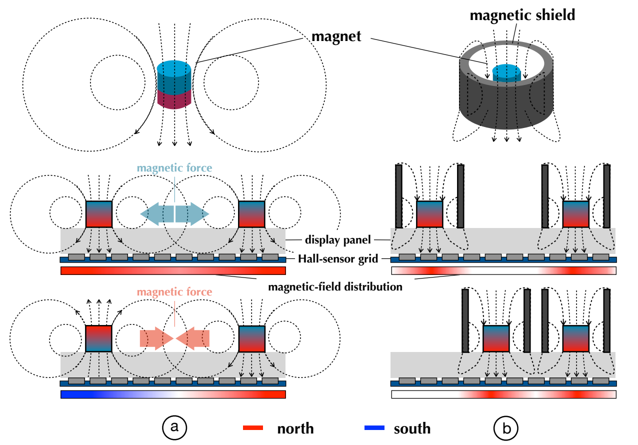

Figure 2. Visualization of magnetic forces and magnetic fields (a) without magnetic shield and (b) with magnetic shield.

Imaging sensors such as optical cameras or analog Hall-sensor grids can also be used to enhance the object tracking capability of portable displays and do not require hardware modifications. Portico [1] mounted two cameras above a display to track visual markers on a screen and on the surrounding surface. Top-down detection methods were sensitive to environmental light and hand occlusion, which limited the form factors of the token and degraded the user experience. Although the occlusion and lighting issues can be mitigated by back-of-device or in-cell optical sensing methods, e.g., ThinSight [10] and MightyTrace [7], which can track multiple on-screen tangibles attached to reflexive markers on its bottom, e.g., SLAP [23], these technologies require considerable hardware modifications.

The GaussSense [15] analog Hall-sensor grid is a portable and occlusion-free imaging sensor that enables monitoring of multiple magnetic tangibles on and above a portable display [14]. It resolves the geometry of a construction of multiple magnetic building blocks in real-time [13] and can be easily attached to the back of a portable display. However, magnetic forces raise issues of interference and identification in multi-token applications. Figure 2a shows that several magnetic tangibles placed on a display surface tend to attract or repel each other, which impedes user interactions. The magnetic fields also merge with or counteract each other,

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

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

which invalidates the sensing of position, orientation, and ID information. Proposed solutions such as using non-ferrous constraints or adding weight and friction pads on the bottom of tangibles to separate the magnets from each other [14] increase the size and weight of the tokens, which is inappropriate for small portable displays and multi-token applications. Hence, multi-token applications must be composed of a new material.

UNDERSTANDING MAGNETIC SHIELDING

Principles of Magnetic Shielding

Multi-token interactions are facilitated by using magnetic shielding to mitigate interference between magnetic tangibles. Magnetic shielding is widely used to protect electronic components from electromagnetic (EM) interference. However, thin magnetic shields cannot effectively block magnetostatic fields, which have stronger penetrability. Therefore, the most effective way to shield magnetostatic fields is by *redirecting* them rather than by blocking them.

Eliminating this interference required a case composed of highly permeable material, such as galvanized steel, mumetal, etc. In this study, the magnet was affixed to the inside of the case as shown in Figure 2b. The case absorbed magnetic fields by attracting nearby magnetic flux, which allowed the flux to flow through the surface of the case and prevented the magnetic flux from penetrating. The magnetic shield enabled magnetic objects to be placed close to each other without affecting the signal quality or the physical state.

In addition to using highly permeable materials, another important factor is the geometry design of the shields. An inappropriate geometric design may fail to eliminate interference and may even block signals and make them invisible to magnetic field sensors. To understand how to provide a shielding mechanism that effectively maintains the quality of the signal source, a series of formal measurements were performed to establish parameters for an effective shielded magnetic tangible design.

Explorative Study

Apparatus

According to the definition of shielding factor in [20], shielding capability depends on the dimensions of the shield. Figure 3a shows the nine different shielded magnetic token types that were measured. The tokens were 1.5cm(W)$\times$1.5cm(H) acrylic cuboids, each of which contained a N35-class neodymium magnet (radius, 2.5mm; height, 1cm). The magnets were fixed to the acrylic cases. Several 1.5mm(W)$\times$1.5mm(H) galvanized steel chips were cut from 1.2mm-, 2mm-, or 3mm-thick galvanized steel sheets and attached to the tokens to provide shielding. Since only two of the six faces were shielded, the shapes of the magnetic fields could be observed on the unshielded faces.

Figure 3b shows the 32x32 = 1024 Winson[3] WSH138 analog Hall sensors with a 16(W)$\times$16(H) cm^2 sensing area, which were mounted as a grid to capture the magnetic-field image of the shielded magnetic tokens. Each sensor element detects

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

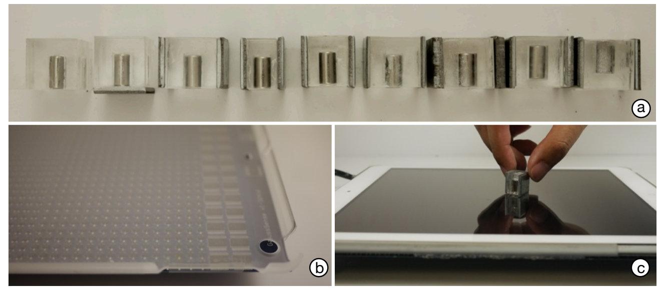

Figure 3. (a) Shielded tokens for testing. (b) Analog Hall-sensor grid. (c) Measurement platform.

both N- and S-polar magnetic field intensities in a range from 0 to 200 gauss on a 256-point scale and at a sampling rate consistently higher than 40 fps. The N- and S-polar magnetic fields at each sample point are mapped to a red or blue color intensity of the corresponding pixel on a 310 px$\times$310 px bitmap, respectively. The sensitivity of the Hall-sensor grid is calibrated using the method presented in [13]. The analog Hall-sensor grid is attached to the back of a 7.9mm-thick iPad Air tablet (Figure 3c). Alternatively, a 3mm-thick acrylic sheet can be used as the measurement platform.

Task and Procedures

The measurement was performed in two parts. The first part measures the magnetic fields horizontal to the magnetic dipole vector. After the shielded tokens were laid down, the tokens on the 3mm-thick acrylic sheet are measured. The second part was measuring the magnetic fields vertical to the magnetic dipole vector. After the shielded magnetic tokens were erected, the tokens on the iPad Air were measured. Each unit was measured by arbitrarily moving it on the surface of the 16$\times$16 cm^2 sensing area. For each unit measured, 1000 samples were captured. The analysis included 2 (parts) $\times$ 9 (units) $\times$ 1000 (samples) = 18000 bitmaps of magnetic-field images.

Data Processing

The distribution of the magnetic fields was observed by using several thresholds of magnetic field intensity for N(orth) and S(outh) fields, $T_{N,i}$ and $T_{S,i}$, where $T_{x,i} = T_{x,i-1}$+10 gauss for all $i > 0$ and $x \in \{N,S\}$, to extract the corresponding N-pole and S-pole blobs from the magnetic field image. For each sample, the blob size and maximum N-field and S-field intensities were recorded.

Results and Findings

Figure 4 to Figure 7 show the complete results. For all samples, the x-y plane plots the mean values and ranges for two standard deviations of blob sizes. The horizontal axis plots the means and the range of two standard deviations of N-field and S-field intensity. This format is used to visualize the implementation throughout the following discussion. In addition to the statistical data are the sample raw data, which are aligned and visualized underneath the token, to illustrate further information that is not shown in the statistics. Based on the results, the four main findings of the study and guidelines for designing shielded magnetic tangibles are summarized.

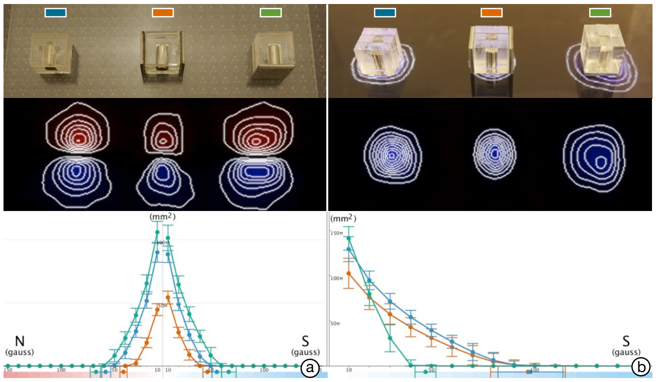

Figure 4. Experimental results for different shielding methods. (Blue) Un-shielded. (Orange) Shielded on the side. (Green) Shielded on the bottom. The distributions of magnetic fields as sensed and visualized from (a) the sides of the tokens, and (b) the bottoms of the tokens.

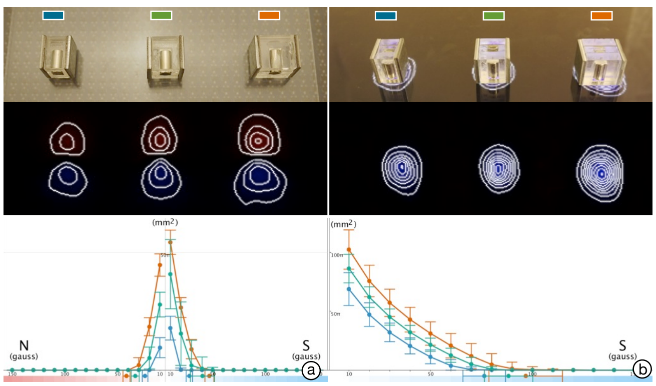

Figure 5. Experimental results of different gap distances between the magnet and the shield. (Blue) 2mm (Green) 3.5mm (Orange) 5mm. Distributions of magnetic fields] sensed and visualized from (a) the sides of the tokens, and (b) the bottoms of the tokens.

1. The shield should be in parallel to the magnetic dipole. Figure 4 shows that the shielding is highly effective when it is parallel to the dipole vector of the magnet, and signal strength is unaffected if the shield is] an adequate distance with the magnet. In contrast, the shielding is ineffective when the shield is directly attracted by the dipole of the magnet, which also reduces signal strength.

2. Decreasing the gap between the magnet and the shield reduces signal strength. Figure 5 shows that decreasing the gap significantly reduces the blob sizes in both measurements, which confirms the effectiveness of the mechanism. The experimental results show that a user can make smaller shielded magnetic tokens by using smaller shields. The results also imply that the magnet should be positioned horizontal to the center of a token to ensure the similar capability of shielding in all directions. Nonetheless, as the gap distance decreased, the signal strengths significantly decreased as well. Consequently, stronger or larger magnets may be needed to compensate for] the loss of signal strength.

3. Increasing the shield thickness improves shielding quality without affecting the signal strength. Figure 6 shows that the shield thickness does not significantly affect the blob size or

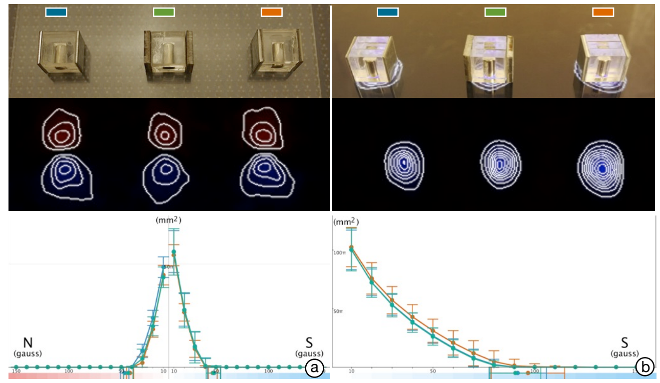

Figure 6. Experimental results for different shield thicknesses (Blue) 1.2mm-thick. (Green) 3mm-thick. (Orange) 2mm-thick. The distribution of magnetic fields as sensed and visualized from (a) the sides of the tokens, and (b) the bottoms of the tokens.

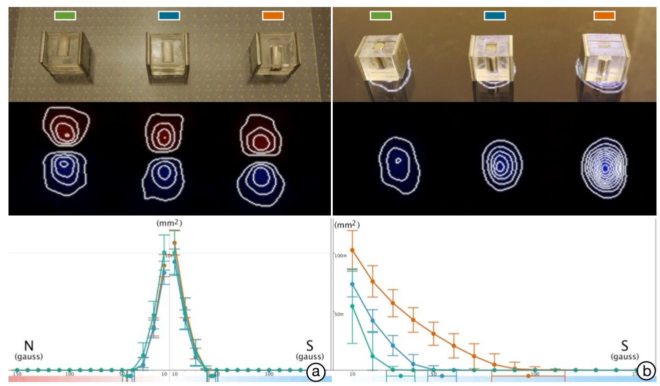

Figure 7. Experimental results for different vertical distances between the magnet and the sensor: (Green) 5mm, (Blue) 2.5mm and (Orange) 0mm from the bottom. The distributions of magnetic fields as sensed and visualized from (a) the sides of the tokens, and (b) the bottoms of the tokens.

signal strength. However, the raw data indicate that a thicker shield is better in terms of locking the magnetic fields even though the blob size does not decrease in statistics. The experimental results suggest that, if the shielded tokens must be placed very close to strong magnets in the shield, thicker shields are preferable.

4. Stuffing magnets deep inside the shield does not affect shielding but reduces the signal strength. Figure 7 shows that stuffing magnets deep inside the shield does not affect shielding strength. However, since it substantially reduces signal strength, larger or stronger magnets may be needed. Therefore, rather than increasing the depth of the magnets, positioning a small magnet as close as possible to the surface would be more effective way to control token size as well as the signal strength.

Summary

This study explored several possible design parameters, excluded several inefficient parameters, and identified shield dimension, shield thickness, and magnet strength as efficient parameters when designing shielded magnetic tangibles. Small shielded magnetic tangibles require both stronger

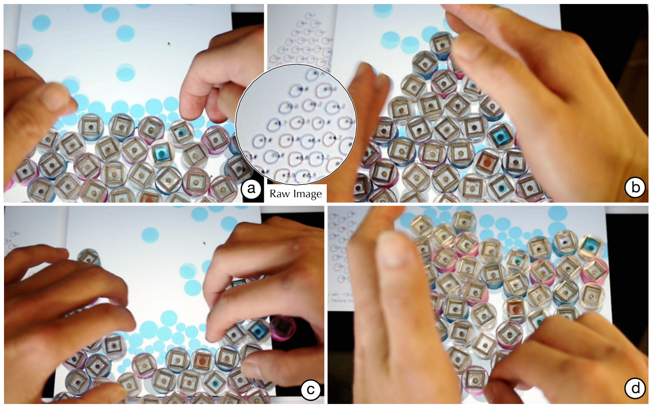

Figure 8. (a) For sculpting and simulation applications, users can shape the particles by 3D hand gestures such as (b) building a mountain, (c) digging a valley, or (d) making favorable shape. Simulation results respond to the shape in real time.

magnets and thicker shields to keep both shielding and signal valid. This requirement is a design constraint in shielded magnetic tokens. In contrast, large shielded magnetic tokens have relatively few constraints and allow for adjustment of the relationships between shield dimensions and thicknesses to create different magnetic field distributions or intensities for advanced sensing. The next section introduces the design and application of the smallest token design and then gradually relaxes the size constraint to provide a larger design space.

DESIGNING GAUSSSTONES IN DIFFERENT SIZES

This section introduces designs for different-size GaussStones to fit the requirements of different applications. The three categories of GaussStone designs are 1) particles, 2) tokens, and 3) knobs. An iPad Air and a macbook pro display with a 2mm-thick analog Hall-sensor grid attached to the back are used for presentation.

Designing GaussStones as Particles

Small particles can support applications that requires fine manipulation, such as sculpting [6] or geographic simulation [18]. Figure 1a shows the smallest shielded magnetic particle obtained for the presentation platform (radius, 7.8mm; height, 10mm; weight, 6g). Inside the particle is a 1cm$\times$1cm cuboid shield composed of 4 pieces of 2mm-thick rectangular galvanized steel sheet. Inside the shield is a 2mm-radius(W)$\times$5mm-radius(H) cylindrical neodymium magnet, which is fixed to the center bottom of the shield by a laser-cut acrylic case. The shielded magnet is encapsulated in a 7.8mm-radius$\times$1cm-height acrylic cylinder, which functions not only as a safety gap to ensure reliable detection, but also as a favorable shape for manipulation.

Sensing the particle position

The system tracks the on-screen position of the particles by analyzing the obtained bi-polar magnetic field image. A noise intensity threshold is first used to separate all connected components and remove the unwanted noises. All connected components are then extracted from the magnetic field image regardless of the polarization. The centroid of each component is used to represent a particle position.

Figure 9. (a) In a checkers game, two types of tokens, S-type (blue) and N-type (red), are clearly distinguishable. (b) When the token is lifted, the display provides hints for the possible landing position and the possible threats from the opponent. (c) Visual hint for removing the defeated piece.

Application: Sculpting and Simulation

The sculpting and simulation application (Figure 8) allows a user to place a maximum of 100 particles in the sensing and display area. In the display area, users gather bunches of particles and use their hands to shape the particles into terrain features such as mountains or valleys. Then, users can activate the raining simulation, letting the raindrops fall into the built terrain. As the user changes the terrain, such as separating the valley to let the rain drain away, the simulation responds in real time. Since the particles are physical, sculpting with tangible particles provides useful haptic feedback. Users can perform the task naturally or freely improvise as they would in the physical world.

Designing GaussStones as Tokens

The two polarities of each magnet have the same intensity. Hence, simply flipping the magnet within the particle creates a paired set of data, which requires no modification on the geometry design of the shield. The token position is sensed using the same method used to sense particles, but the polarization, North and South, is now used to recognize the tokens as N- and S-type, respectively.

Application: Board Gaming

In a checkers game (Figure 9), 12 S-type tokens and 12 N-type tokens are placed on each side of the checker board. In each round, the player grasps the tokens to move diagonally from one square to another square. When a token is lifted from the display, the system gives a visual hint for the possible positions and possible threats of opposing pieces on the display. If the opponent places a piece in the wrong position, the system ignores the move and continues waiting for the right player to put his/her piece on it. When a player jumps over an opposing piece, the system recognizes the move and prompts the user to remove the defeated piece to move the game forward. The same concept is applicable to board games that use only two token types, e.g., Othello, Abalon, Gomoku, etc.

Identification using Magnetic Field Intensity Distribution

For applications that require tokens that contain or represent information, the tokens require features for identifying themselves. Small field shapes and intensities of particles are too weak to carry additional ID information. Using stronger magnets or using thinner shields can increase the magnetic field intensity, but also reduces the effectiveness of the shielding. Hence, another finding of the exploratory study is that a larger token is needed.

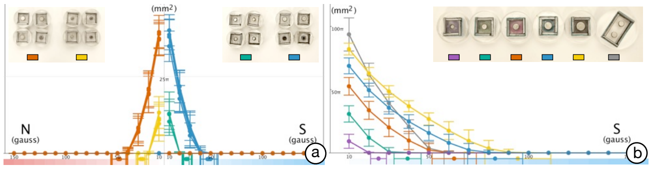

Figure 10. Area-intensity profiles of the two sets of ID. (a) Sixteen 8.6mm-radius tokens are clearly classified into four IDs. The area-intensity profiles of tokens in the same ID are very similar. (b) Five S-type 12mm-radius tokens and one 15mm-radius token are clearly differentiated into six IDs.

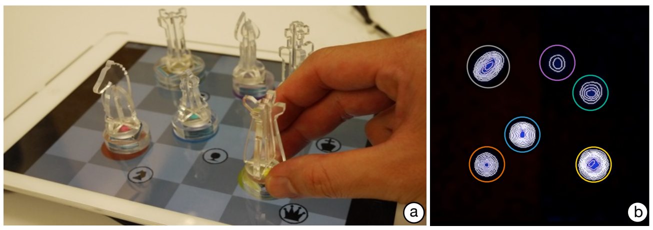

Figure 11. Chess game. (a) All chess types of a player are represented by six S-type tokens. (b) Image of corresponding magnetic field, which is locked inside each token.

Therefore, two sets of GaussStone designs were implemented to test the concept of coding additional IDs by using magnetic field intensity and shape. Figure 10a shows the first set, which has a 8.6mm-radius and consists of a 1.1cm×1.1cm cuboid shield made of 1.2mm-thick rectangular galvanized steel sheet. Two types of cylindrical magnets (height, 5mm with radius, 1.5 and 2mm) are stuffed to provide 2 intensities. The application of this token type is discussed in the next section (Figure 13a). The second set, which has a radius of 12 mm, consists of a 1.4cmx1.4cm cuboid shield made of 2mm-thick rectangular galvanized steel sheet. Five types of magnets can be stuffed (height, 5mm-height and radius, 1.5,2,2.5,3,3.5mm) to provide five distinguishable blob sizes (note that the intensities of the five types are not fully distinguishable), as shown in Figure 10b. The cylinders in both GaussStone types are 1cm high. By building the token in two polarities, the two token types can provide 4 and 10 IDs.

Beside magnetic-field intensity, the magnetic field shape is another potential dimension of ID design. The rectangular shield in Figure 10b fixed two nearby magnets in it creates a magnetic field with a new shape and a unique distribution of blob areas, which are easily differentiated from the tokens consisting of only one magnet. This unique *area-intensity profile* allows the system to classify and identify tokens. (Figure 11) shows that six IDs for both N- and S-type are sufficient for playing a chess game.

Identifying Tokens Using Area-Intensity Profile

Figure 10a shows that magnetic tokens with the same specifications have similar distributions of magnetic field intensity, thus are regarded as the same class. After selecting one token from each class, the same data collection and processing method introduced in EXPLORATIVE STUDY was applied to obtain 1000 samples. In each sample, several different thresholds were used to extract the blobs, and the sizes of the blobs were calculated. For each threshold, the mean blob size and standard deviation were calculated for all samples. Figure 10 shows the area-intensity profiles for the classes of ID, which were based on the obtained mean and standard deviations.

After a token is placed on the display platform and the sensed intensity value stabilizes, the system finds the profile most similar to that of the current token and assigns the ID of the profile to the token. Once the token is identified, it allows for near-surface interactions such as hover [14]. The ID is kept until the token is removed away from the display surface. Based on the simple classification mechanism used herein, all tokens presented in the applications were reliably recognized with near-zero false recognition rate.

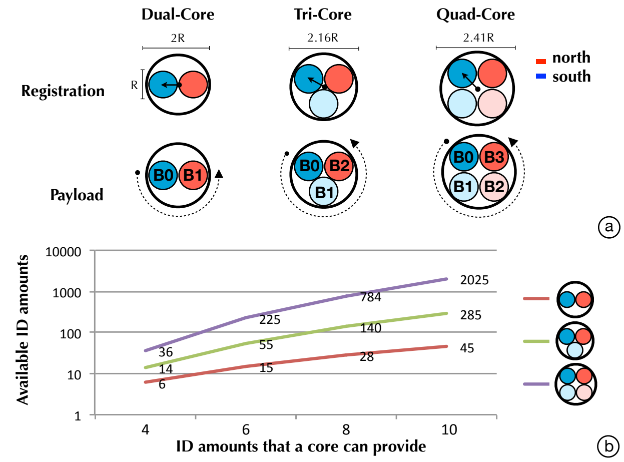

Figure 12. (a) The ID methods for the dual-, tri-, and quad-cores knobs. (b) Available number of IDs according to number of cores and number of IDs provided by a core.

Designing GaussStones as Knobs

In addition to 1D and 2D translation, tokens that support 1D rotation can function as knobs to provide an additional 1 degree of control. The knob was easily built by combining shielded magnetic cores as shown in Figure 12a.

Since the magnetic cores inside the knob do not affect each other, each of them can function as an unique payload bit. Combining at least two IDs provides a feature for registering the location and orientation of the ID. The location is defined by the centroid O of the inscribed circle of the combination. After representative target P, for example, the magnetic core, which has the smallest value $v = I_N - I_S$, where I_N and I_S are the maximum intensities in N- and S-fields, respectively, is used to define the orientation of the knob as $\vec{OP}$.

The magnetic cores also provide information used to identify the token. When the cores are identified, the system can extract the payload bits of the knob in a numerical series from B_0 to B_{k-1} in a k-core knob, as shown in Figure 12a . Each bit is reported as n if the core has n-th largest value v. The ID of a k-core knob ID_{knob} then is decoded as:

$$ID_{knob} = \sum_{i=0}^{k-1} B_i * (N_{core})^i, \quad (1)$$

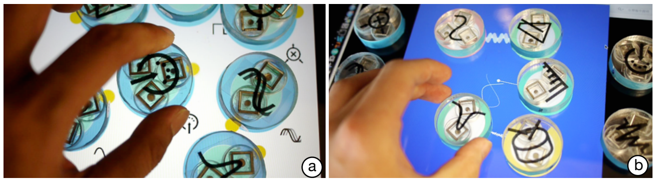

Figure 13. (a) Each dual-core and tri-core token provides its ID, position, and orientation information. (b) Live music performance application.

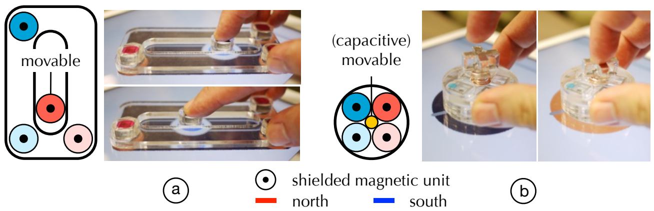

Figure 14. Two sample multi-part widget designs. (a) Slider. (b) Knob with a button.

where N_{core} denotes the number of IDs that a core can provide. However, since an asymmetric ID is needed to provide orientation information, the available ID amount N_k of a k-core knobs can be derived as:

$$N_k = \sum_{i=1}^{N_{core}-1} (N_{core} - i)^{k-1}, \tag{2}$$

where N_{core} denotes the number of IDs that a core can provide. Notably, knobs with different numbers of cores have different ID spaces. Thus, they can be used simultaneously. Figure 12b shows that increasing the number of cores and the number of IDs that a core can provide both increase the ID space. Nevertheless, either increase would result in an increased token size. Designers can choose the suitable design based on the number of IDs required by the application.

Application: Live Music Performance

Figure 13 shows the music performance workbench, which was similar to ReacTable [11]. Twelve dual-core or tri-core knobs on the display represent different tools that can be used for controlling or synthesizing music. To add a patch, a music clip, or an effector into the show, the user can place the corresponding knob on the portable display, arrange the geometric relationships with other tokens, and rotate the knob to adjust the parameter. Multiple users can also stand near the portable display to jam and collaborate with each other.

DISCUSSION

Possible Generalizations

Designing GaussStones as Multi-Part Widgets

As in SLAP widgets [23], it is feasible to design GaussStones with multiple parts and with larger widgets that contain both ID and movable parts. Multi-part widget designs require shielded magnetic units in both ID and movable parts to avoid interactions between the two parts, as the slider design shown in Figure 14a. In capacitive multitouch displays, it is also feasible to make movable parts conductive and the ID part magnetic since the two sensing methods do not interact, as the knob with a button design shown in Figure 14b. Fusing conductive and magnetic parts for multi-part widget designs can further reduce the required widget size so that more widgets can be kept on the small display surface.

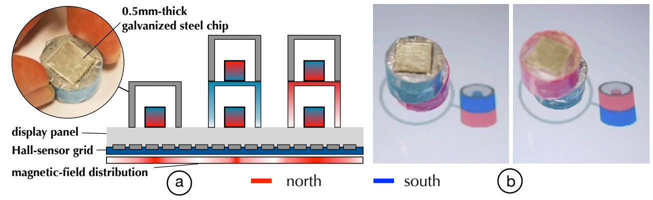

Figure 15. Stackable token design that allows for resolving stacking structures. (a) Visualization of magnetic fields. (b) Results.

Stacking GaussStones

Stackable GaussStones can also be built as GaussBricks [13] since stacked tokens with the varied magnetic-field strength can be used to identify stack operations. In stackable token design, the geometry alignment should be considered. Since the ferrous shielding may attract the magnetic core, and the magnets in different polarities can not attract to each other and cause unexpected results, users can add a thin (0.5mm-thick) galvanized steel chip (Figure 15a) on the top of the token to force the alignment. The stacking token magnetize the underlying token's galvanized steel chip and shield, strengthen or weaken its magnetic field strength according to the polarity. The increase or decrease of the sensed magnetic field strength thus can be used to identify the stacking token, as shown in Figure 15b. The system recognizes stacked structures by up to two layers. Similar to the knobs, combining multiple stackable cores as a unit allows for resolving additional identities while stacking.

Scalability and Limitation

The two main factors in the scalability of the proposed system are particle size and display platform thickness. Regarding particle size, given the fixed resolution of the Hall-sensor grid (26dpi before 10x up-sampling), a particle with a 7.8mm (0.3inch)-radius was the smallest valid particle for both shielding and sensing on the tested platform, 7.9mm-thick iPad Air. Using higher density sensor grids or thinner displays can obtain smaller particles by enabling use of smaller magnets and thinner shields. Regarding the thickness of presentation platform, the system effectively identified the particles and knobs on displays with thickness ranges of 0.3 - 1.0cm with calibration. Displays outside this range of thickness may require sensors with different sensitivities and/or magnets with different strengths. However, since using stronger magnets requires a stronger shielding mechanism, which increases the size and weight of tokens, the proposed technique should be applied in thin-form displays.

CONCLUSION

This work presented *GaussStones*, a system of shielded magnetic tangibles that improves support of multi-token applications by portable displays. The findings of this exploratory study showed that the range of design space of the shielded magnetic tangibles is relevant to the size of token. The use of different token sizes on portable displays was then discussed, including using GaussStones as particles for sculpting and simulation, using the identifiable GaussStones for board-gaming, and using rollable GaussStones for live music performances. These proposed applications are fundamental and essential to demonstrate the potential use of the proposed new magnetic-composite material, which unlocks new applications of tangible interaction design on portable displays.

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