GaussBricks: Magnetic Building Blocks for Constructive Tangible Interactions on Portable Displays

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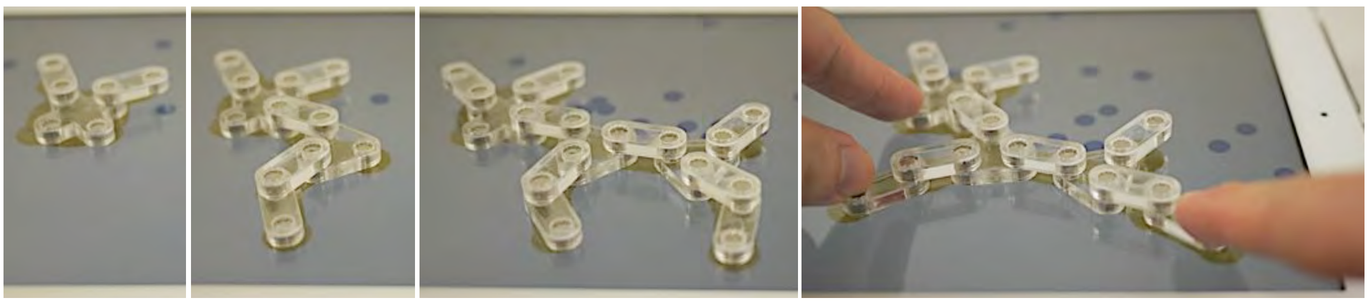

Figure 1. As a system of magnetic building blocks, *GaussBricks* facilitates constructive tangible interactions on portable displays. The Hall-sensor grid mounted to the back of the display derives the geometry and skeleton of the physical structures in real time.

ABSTRACT
This work describes a novel building block system for tangible interaction design, *GaussBricks*, which enables real-time constructive tangible interactions on portable displays. Given its simplicity, the mechanical design of the magnetic building blocks facilitates the construction of configurable forms. The form constructed by the magnetic building blocks, which are connected by the magnetic joints, allows users to stably manipulate with various elastic force feedback mechanisms. With an analog Hall-sensor grid mounted to its back, a portable display determines the geometrical configuration and detects various user interactions in real time. This work also introduce several methods to enable shape changing, multi-touch input, and display capabilities in the construction. The proposed building block system enriches how individuals interact with the portable displays physically.

Author Keywords
Magnetism; Tangible Interactions; Constructive Assembly; Portable Displays

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

INTRODUCTION
Constructive assembly is a major genre of tangible user interfaces (TUI) [11]. Users can easily assemble building blocks to construct a new form [1]. Incorporating mechanical joints with the form further also creates expressive movements [23]. Users, especially children, can intuitively use the tangible pieces in their hands to learn physics-related concepts and explore geometrical concepts through direct manipulation. These digital manipulatives [25] have become highly useful tools for education and entertainment purposes.

Portable displays are easily accessible platforms for general users. TUI researchers have developed several features for portable displays based on capacitive tracking [6, 32], optical tracking [2], and magnetic tracking [4, 15] to allow users to more flexibly grasp tangible handles in order to manipulate high-fidelity display contents. Despite various spatial operations (e.g. translating, rotating, tilting and hovering tokens on the display), users are still unable to construct the form of tangible objects on the displays, because the platform cannot determines the geometrical configuration of the tangibles efficiently, warranting the development of new materials and methods that enable constructive tangible interactions on portable displays.

GaussBricks: Magnetic Building Blocks
This work presents *GaussBricks* (Figure 1), a system of magnetic building blocks that allow users to construct a tangible form on the displays. Each magnetic building block containing strong magnets is designed simply to facilitate configurable and stable form construction. The physical form constructed by the building blocks, which are connected by magnetic joints, supports high degree-of-freedom (DOF) shape

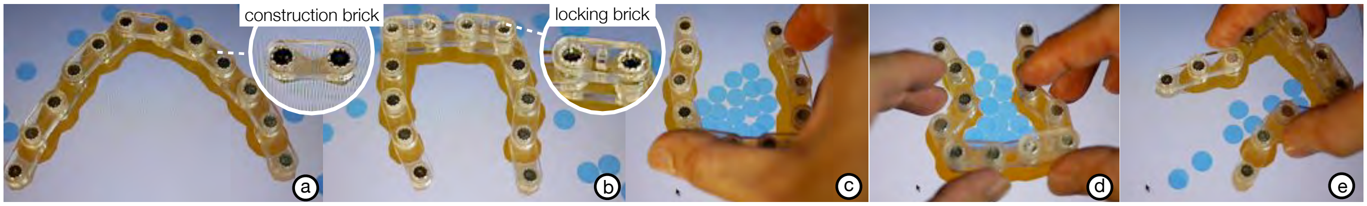

Figure 2. Construct tangible form for physical simulation in the following steps: (a) Use *construction bricks* to construct and shape articulated physical structures on the display. Balls in the simulated gravity bounced away when colliding with the physical structure. (b) Use *locking bricks* to rigidify parts of the construction. (c) Holding the rigid parts to perform spatial operations without affecting the structure. (d) Shape the non-rigid part to facilitate further manipulations, such as (e) pouring the balls.

manipulation and provides rich elastic haptic feedback. With an analog Hall-sensor grid attached to the back of the portable display, the geometry and skeleton of the construction as well as the user interactions can be derived in real time.

Figure 2 displays an example of GaussBricks assembly for physical simulation. To understand Newton's laws of motion, users place a physical structure built by *construction bricks* on the display and then adjust the shape using their hands. Based on the simulated gravity on the display, users trigger the balls to fall down. While colliding with the physical structures, the balls bounce away. To change the direction in which the balls bounce, users snap more bricks to the structures, remove unwanted bricks from the structures, or deform the physical structures. Users move the structures without affecting their geometry by locking some joints. This is achieved by adding *locking bricks*, where the non-rigid parts remains deformable, allowing for shaping the desired affordance to facilitate further manipulations.

Above example highlights the manual construction and manipulation of structures. While easily scalable and maintained, the passive building blocks support hybrid construction of rigid and non-rigid structures, allowing for spatial operations on the construction with rich force feedback.

Besides forming, users can construct elastic structures by using the proposed GaussBricks system, as well as design a physical form for near-surface interactions. By integrating with other components or materials, GaussBricks can be extended for advanced applications, such as building mechanical responsive structures by incorporating actuators, enabling multitouch inputs on the construction by applying conductive coatings, and enhancing display capabilities on the bricks by using fiber optics. Above results provide a valuable efforts to highlight the novel interactions enabled by using the proposed magnetically composite material.

The major contribution of this work is introducing the novel material, GaussBricks, which supports stable, configurable, and interactive form construction on portable planar displays with wide applications.

The rest of the paper is arranged as follows. Related work is discussed first. Then, we explain the physical design of GaussBricks and realtime sensing schemes, as well as implementation details and evaluation. Then, we describe several examples to highlight the basic features of this building block system. Then, we present several methods that extend the interactivity of the GaussBricks to a wider context. Conclusions are finally drawn along with directions for future research.

RELATED WORK

Constructive assemblies of modular, interconnecting elements greatly facilitate physical modeling and geometrical representations, including LEGO[1], Meccano[2], and ZOOB[3]. Physical building blocks allow for quick construction and manipulation of structures through two-handed interaction [8]. To fully exploit the use of building blocks as tangible user interfaces (TUIs) [12], Topobo [23] allows users to create 3D structures by assembling passive pieces with motor joints, and editing the structures' motions by direct input with kinetic motion as output. Kinematics [18] extends the Topobo concept by providing computational blocks to allow for editing movements without programming. Bosu [19] provides a toolkit for users to construct curve forms and structures. However, owing to that these methods are unaware of their own structures, users cannot interact with a display without external detection supports when using such methods.

While recognizing the structure of an assembly can enable broader applications, Anderson *et al.* [1] embed connectors and micro-controllers into each building block to allow for interpretation of the geometrical configuration of an assembled physical model. ActiveCubes [28] allows users to assemble different electronic elements in order to increase functionality. Siftables [17] detects the geometrical combinations of display blocks and supports embodied gestures such as knocking the table to shuffle the contents displayed on every block. Despite the ability of active building blocks provide rich interactivity, the electronic elements require additional maintenance, making it difficult for them to achieve scalability as passive building blocks.

Passive building blocks can be recognized by external cameras. By using a top-mounted depth camera, SandScape [20] derives a sand sculpture and building block construction on a tabletop platform. By using an external color+depth camera, DuploTrack [9] monitors the 3D structures of passive building blocks. While attempting to provide increased portability and less effort in calibration, Portico [2] positions two cameras above a display to track the visual markers on a screen and the surrounding surface. Despite their unique features, these top-down detection methods are sensitive to hand occlusions, thus limiting the form factors of building blocks and degrading the user experiences.

[1] http://www.lego.com/
[2] http://www.meccano.com/
[3] http://www.infinitoy.com/zoob/

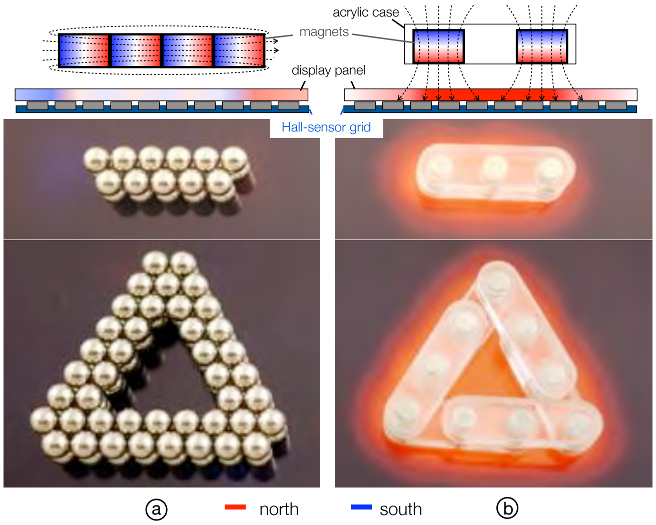

Figure 3. Magnetic fields shaped by two construction methods. (a) Non-uniform magnetic fields caused by attracting the magnets. (b) Uniform magnetic fields shaped by firm casing. A laptop display mounted with an analog Hall-sensor grid visualizes N- and S-polar magnetic field intensity maps in red and blue, respectively.

Several methods feasibly alleviate the visual occlusion problems while allowing for constructive assembly. Lumino [3] introduces the fiber optics block design to allow the markers of stacked objects to become visible for a diffused-illumination tabletop, or an in-cell optical multitouch displays such as ThinSight [10] and PixelSense[4]. For more portable capacitive multitouch displays, Capstones and ZebraWidgets [6] extend the Lumino concept to enable stacking and several 1D operations such as translating and rotating on the stack, based on the foundations of capacitive tangible designs established by SmartSkin [24] and TUIC [32]. Voelker *et al.* [14] further presents PUCs to demonstrate the feasibility of detecting the capacitive tangibles while remaining untouched and made transparent by applying indium tin oxide (ITO) coatings. Based on pressure images, Geckos [13] allows for stacking on an easily portable IFSR [26] multitouch panel. While unable to resolve problems involving the overhanging structures of a stack, above approaches only support constrained 1D operations such as stack rotation. To our knowledge, the design spaces of 2D constructive assembly and further shape manipulation have not been investigated.

Analog Hall-sensor grid, GaussSense [16], a portable imaging sensor, allows for monitoring of multiple magnetic tangibles on and above a portable display [15]. A thin Hall-sensor grid can be attached to the back of a device to incorporate with the portable capacitive touchscreen as an additional channel of sensing. In contrast to capacitive- and optical-based methods, magnetic object tracking of this method is occlusion-free and independent of touch sensing. The Hall-sensor grid robustly detects and resolves problems associated with the magnetic fields' shape, polarity, and intensity of the magnetic tangibles that those users' hands are interacting with. This grid also prevents interference with the object tracking when users' hands or fingers touch the screen accidentally. These features are highly desired for sensing interactive constructions.

[4]http://www.microsoft.com/surface/

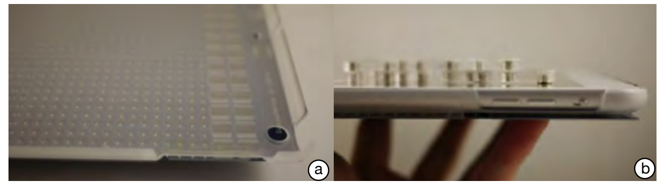

Figure 4. Sensing platform. (a) Analog Hall-sensor grid. (b) Portable display with a Hall-sensor grid attached to the back is used as interaction platform.

Magnets initially appear to be highly desired materials for tangible construction, because the different-pole magnetic tangibles are naturally attractive to each other, subsequently forming a sense of connection. However, the resulting complex magnetic fields through the connections may not follow the geometry of the construction, or even become invisible to the Hall-sensor grid (Figure 3a). Therefore, exactly how to enable constructive tangible interaction using magnets remains unclear.

SHAPING THE MAGNETIC FIELDS

The magnetic fields of each unit must be shaped before use to ensure reliable tracking of the construction of magnetic units. Shaping a usable magnetic field depends on the ability to *keep the construction's magnetic field in the same polarity*.

An axial-magnetized cylindrical neodymium magnet is used here as the signal source since its physical form allows use of a firm case to fix its direction (Figure 3b). Axial-magnetized cylindrical neodymium magnet provides a uniformally cylindrical and symmetrical magnetic field, which is also a desired property of a signal for magnetic field sensing. The acrylic case for the magnets is then built to fix their positions in the same distance with respect to each other. The distance between magnets is set to be sufficiently small in order to merge the magnetic fields from individual magnets into a continuous shape, which is topologically equivalent to the structure of the physical construction. The shape of a magnetic field is now usable for deriving the geometry of the construction.

DESIGNING MAGNETIC BUILDING BLOCKS

The principle of designing a building block system is keeping it *simple*, *stable*, and *transparent* in use. Providing simple units with minimum physical connection allows for configurable construction to support users' creativity [1]. During construction, the physical model must be kept as stable as possible [22]. Since the building blocks are designed for construction on the display, ensuring that the building blocks are transparent allows users to perceive the underlying display contents more easily [29].

Based on above three principles, we demonstrate the feasibility of three magnetic building blocks made by transparent acrylics: *construction bricks* (Figure 5a), *supporting bricks* (Figure 5b), and *locking bricks* (Figure 5c). These bricks are designed for additive construction, stabilization, and rigidifying construction, respectively. A 2mm-thick analog Hall-sensor grid mounted to the back of an iPad display (Figure 4) is used here as the presentation platform.

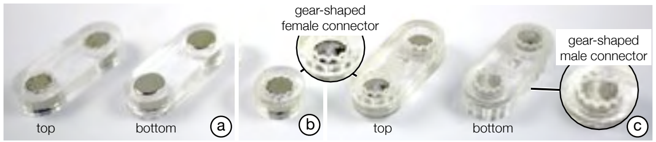

Figure 5. Three basic building blocks are (a) *construction brick* for additive construction, (b) *supporting brick* for stabilization, and (c) *locking brick* for rigidifying structures. The gear-shaped male connectors underneath each locking brick can fix the joint in 12 angles by inter-locking with the female connectors on the top of each brick.

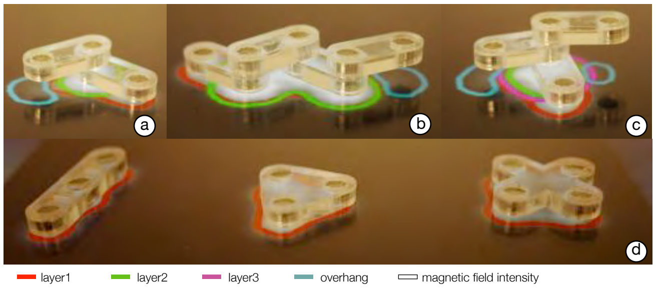

Figure 6. Use cases of construction bricks. (a) Connect the construction bricks by stacking using the magnetic attraction force. The geometry and composition of the structure can be derived by the resulting magnetic field intensity. (b) Create additional degrees of connection by (b) chaining or (c) stacking. (d) Optional construction bricks allow for further configurable construction.

Construction Bricks

Construction bricks (Figure 5a) are designed for addictive construction. A 1x2 construction brick is made of an easily graspable 2.5cm-length$\times$1cm-width$\times$0.5cm-height round-corner cuboid, which has two 3mm-radius$\times$4mm-height cylindrical neodymium magnets as connectors. According to the measured intensities of the magnets we used, the gap between each magnet can be set in range of 0cm to 0.8cm width to keep their magnetic fields merged together. We set the gap in 0.5cm-width, which not only ensures the reliability of detection but also allows for users to view the underlying display contents between non-transparent magnets.

The magnetic connectors allow users to easily add and remove the bricks by stacking (Figure 6a). Since the building blocks are kept in the same polarity throughout the construction, the validity of the resulting magnetic field is kept as well. The simple round-corner cuboid form also allows two connected bricks to rotate against each other along with the magnetic joint. Each joint adds one degree of freedom to the structures (Figure 6b). Stacking each brick on the joints also adds one degree of connection (Figure 6c). Therefore, the construction bricks allow for creating arbitrary physical structures. We also provide several variations of construction bricks (e.g. 1x3, 2x2, and 3-way bricks (Figure 6d)) to ensure more configurable construction by using fewer bricks.

Supporting Bricks

The form constructed by stacking may have an unstable geometry, making it difficult for users to interact with. *Supporting bricks* (Figure 5b) are therefore designed to support unstable structure. A supporting brick is a 1x1 construction brick with only one connector for stacking, subsequently allowing users to snap it to the bottom of various unstable structures, as shown in Figure 7.

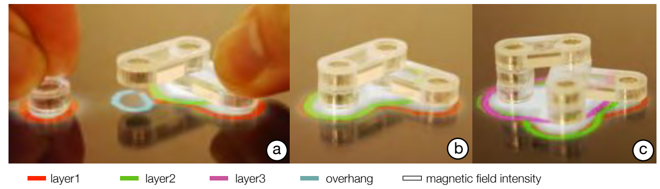

Figure 7. Use cases of supporting bricks. (a) Stabilize the structure by snapping a supporting brick to its bottom. (b) Stack supporting bricks to support the part in higher layer.

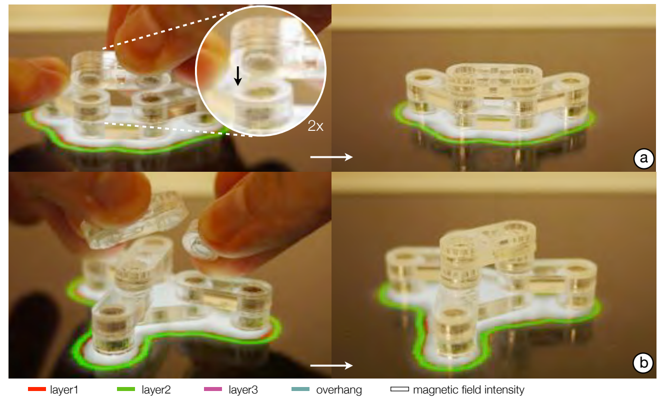

Figure 8. Use cases of locking bricks. (a) Lock the joints by snapping a locking brick on it. (b) Lock the 3-degree joint by combining the 1x1 and 1x2 locking bricks.

Locking Bricks

When the construction consists of many degrees of freedom, users might have difficulty in taking control of them during interaction. *Locking bricks* (Figure 5c) are therefore designed for locking the joint temporally to reduce the unwanted degrees of freedom. A locking brick, in a similar form with a 1x2 constructive brick, consists of a smaller 3mm-radius$\times$2mm-height cylindrical magnet inside and a 1mm-thick gear-shaped male connector on the bottom. The magnets in the locking bricks are small and adequately far from the sensor, thus not affecting the sensing. A gear-shaped male connector is paired with the female connectors preserved on the top of each brick (Figure 8a). When snapping a locking brick on a joint, users can interlock the joint in 12 different angles. Similar to construction bricks, 1x1 locking bricks are also provided to support 1x2 locking bricks for fixing several joint types (Figure 8b).

SENSING MAGNETIC BUILDING BLOCKS

Sensing Hardware

Based on the results of a previous effort [16], we develop an analog Hall-sensor grid (Figure 4a) to track the magnetic structures without interference from user hands and the surrounding environment. The prototype analog Hall-sensor grid consists of 32×32 = 1024 Winson WSH138 Hall sensors, which is measured in 2mm thick with an 16(W)$\times$16(H) cm^2 sensing area.The detected N-polar magnetic field intensities in a range of 0 to 200 gauss are 15x up-sampled to a 465×465 8-bit gray-scale bitmap image with the sampling rate consistently higher than 40 fps. The Hall-sensor grid can be attached to various display platforms, including laptop computer displays or tablet displays (Figure 4b).

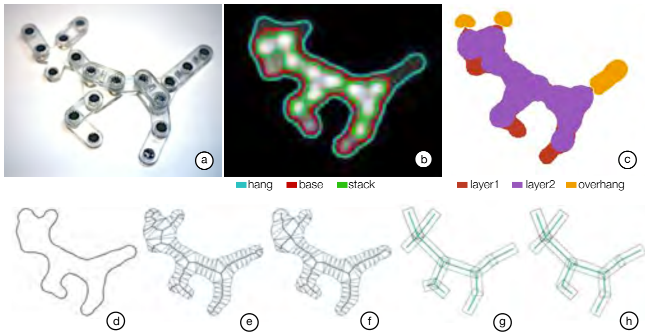

Figure 9. Sensing pipeline of geometry and skeleton extraction. (a) Example model, (b) calibrated magnetic fields and sub-images (denoted as contours in different colors), (c) segmentation results, (d) contour of I_{base} to skeletonize, (e) extracted spine of the triangulated contour, (f) trimmed spine with merged joints, (g) skeleton extracted from the spine, and (h) resulting skeleton after removing unwanted spikes from the joints.

Calibration and Preprocessing

Calibration first involves subtracting the background to eliminate the bias of each sensor element. The difference in sensitivity for each sensor is then determined by moving a 3mm(R)×4mm(H) magnet on the display. Based on the measurement results, the sensitivity of each sensor is normalized.

Sensing Algorithm

A simple pipeline (Figure 9) is designed for extracting the low-level features of the constructions, i.e., boundaries and skeletons, from a raw magnetic field image I_{raw} (Figure 9a). An attempt is then made to recognize different parts of the structures as well as user interactions in I_{raw} by extracting three binarized sub-images, I_{base}, I_{stack}, and I_{hang}, through means of applying several thresholds to obtain different parts of the following structures: T_{base}, T_{stack}, and T_{hang}, respectively, where $T_{stack} > T_{base} > T_{hang}$. I_{base} denotes the parts of structures that are placed on the displays; I_{stack} represents the parts of structures that are stacked in two layers; and I_{hang} refers to the parts of structures that are overhung above the display. Correspondingly, users can freely add different thresholds to extract more sub-images to sense other structural types, such as the components stacked higher than two layers. Next, the connected components of each binarized sub-images are extracted. Too small components are removed and regarded as noise. According to the information in all sub-images, as shown in the contours in Figure 9b, the boundaries, geometrical configuration, and composition of the constructions are roughly determined, as shown in the segmentation results in Figure 9c. These features are sufficient for programming basic techniques (e.g., pattern matching, collision detection, and pressure detection) for users to interact with the display content.

An attempt is also made to support more complex user interactions (e.g., shaping a physical model) by further extracting the skeleton to render a more precise graphical representation under a model. Based on the procedures from Figure 9d to Figure 9h, the rough skeleton of the connected component is first obtained by applying constrained delaunay triangulation on it, by using the algorithm introduced in [21]. The rough skeleton is then processed in the following steps: 1) Merge the joints that are adjacent to each other and trim the unwanted branches that are connected to the boundary; 2) Link the remaining joints and the ends of branches to obtain a simplified skeleton. Lengthy branches can be broken into several segments; and 3) Trim the spikes of the simplified skeleton to obtain the final skeleton. The obtained skeleton not only allows for rendering graphical context precisely on the skeleton, but also support our system in describing user construction concisely.

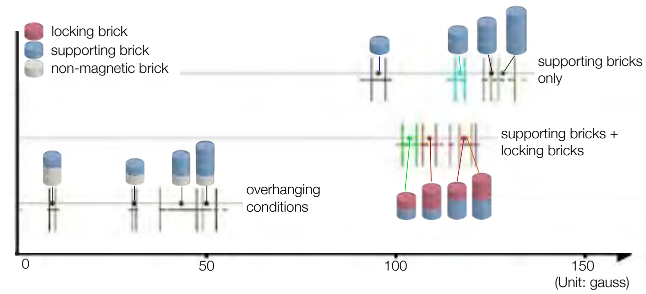

Figure 10. Evaluation results of the measured maximum magnetic field intensities of 12 possible combinations. Data are plotted with the mean value and the covered area of two standard deviation. The proposed system recognizes stack and overhanging structures by up to three layers. Notably, using locking bricks does not affect the recognition accuracy.

EVALUATION

Limitations and robustness of the current system are examined by conducting a formal measurement to evaluate the magnetic field intensity of different components, which is vital to classifying them into different magnetic field images.

Apparatus

The magnetic field intensity is measured by using a 6mm-thick 11-inch Sony VAIO Pro multitouch laptop display mounted a calibrated analog Hall-sensor grid. Twelve possible combinations within four layers of a stack are evaluated using supporting bricks and 1x1 locking bricks (Figure 10). The test cases include four stacking types that use supporting bricks only, four stacking types that use both locking bricks and supporting bricks, and four overhanging structures. Stacking supporting bricks on 5mm-height acrylic bricks that contain no magnet inside simulates the overhanging conditions.

Tasks and Procedures

The maximum magnetic field intensity of each combination is measured at 9 sample points, which are distributed in the 16x16 cm^2 sensing area. One hundred data are sampled at each sample point. A total of 12 (case)×9 (point)×100 (sample) = 10800 data points are collected and plotted with the mean value and the covered area of two standard deviation in Figure 10.

Results

Figure 10 indicates that the proposed platform discriminates up to 3 levels of a stack, as well as 3 levels of overhanging structures. In our test conditions, applying the locking bricks does not affect the sensing robustness. However, some ambiguous results are found when detecting the four levels

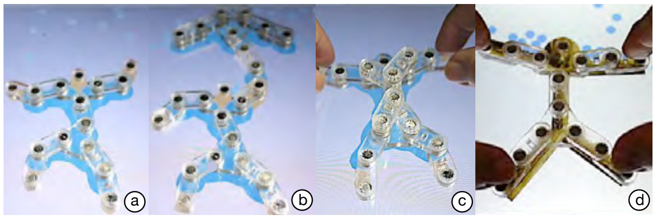

Figure 11. A puppetry storytelling application involves the following steps: (a) assemble a humanoid puppet for mimicking human action, (b) snap an umbrella on the puppet's hand, (c) lock the trunk of the puppet to ease the manipulation, and (d) change the textures rendered on the transparent model.

of stacking and overhanging. This finding suggests that the proposed platform does not support 3D model construction effectively, owing to that it can only be stacked up to 3 levels. Nevertheless, the capability of three levels of stacks is sufficient to support all applications introduced in this work.

BASIC UTILITIES OF THE MAGNETIC BUILDING BLOCKS

This section presents three examples of applications built based on the proposed magnetic building blocks to demonstrate the feasibility of using GaussBricks.

Interactive Form Construction and Manipulation

The proposed sensing platform can derive features involving the boundaries, geometrical composition and the skeleton of the construction in real time, thus providing high interactivity on form construction and manipulation. In the puppetry storytelling application (Figure 11a), users construct a humanoid puppet using the construction bricks to imitate human actions. Users can either customize the appearance of the puppet (e.g., height of the puppet and length of the hand and leg) or add accessories (e.g., an umbrella in the puppet's hand) (Figure 11b). Based on the skeleton captured by the platform, the textures are rendered properly and are easily changeable (Figure 11d). The displayed graphical information reacts properly to the geometry of the construction, as the simulated rains drop on the body bouncing to the ground. In the same manner, users can grasp the physical skeleton to interact with the graphical content in the digital world.

Since the humanoid puppet consists of many joints, users who move it quickly or remove it from the display may cause an undesired change in its physical geometry. To easily control the humanoid puppet, users fix its spine, elbows, or knees by snapping locking bricks on it (Figure 11c). After the joints are locked, users can move the puppet even away from the display surface without affecting the geometry of the locked parts. Users can also manipulate the puppet more comfortably to create expressive movements by using fewer fingers. Users can even fix the entire model by either snapping locking bricks on all joints or removing the locks to free the joints of the desired parts whenever desired.

Constructing Elastic Physical Structures

A physical form that provides rich force feedback allows for more ways of interacting with digital worlds. By further exploiting magnetic forces, which are essentially coupled with magnetic fields, magnetic joints that connect the elements can also act as physical springs to provide various elastic force feedback mechanisms. We briefly introduces several elastic structures that users can incorporate into their constructions.

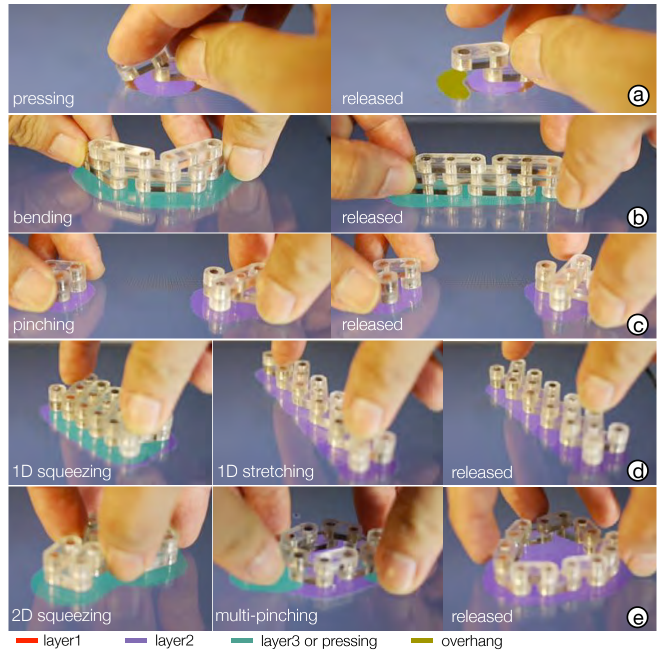

Figure 12. Basic elastic structures based on magnetic forces. (a) Hanging structure, (b) three-layered linear structure, (c) V- (left) and X-structure (right), (d) X-serial structure, and (e) V-closure structure. The performed gestures can be derived by the magnetic field distribution.

Magnetic attraction forces that connect the bricks together maintain the construction's structure. When users deform the structure, the magnetic joints feed the attraction forces back to the users. Structures that use magnetic attraction can provide elastic force feedback on the following two gestures:

Click. The hanging structure (Figure 12a) allows for clicking with elastic force feedback. Similar to clicking a button, users press the upper hanging brick down to the surface and release to recover the position of the hanging brick. The shape of magnetic field conveys state transition-related information.

Bend. The three-layered linear structure (Figure 12b) allows for bending with elastic force feedback. Similar to bending a rubber stick, users bend the three-layered linear structure and release it to recover its shape. Curvature of the shape of magnetic field denotes the pressure asserted by the users. This structure provides the maximum capability of bending.

Magnetic repulsion forces between each magnet keep the bricks away from each other. When users move the magnets close to each other, the magnets feed the repulsion force back to the users. Structures that use magnetic repulsion can provide elastic force feedback on the following three gestures:

Pinch. The V- or X-structure (Figure 12c) connected with two construction bricks allows for pinching with elastic force feedback. Supporting bricks are used to maintain the balance of construction and to prevent the bricks from snapping together. Similar to pinching a clip, users can pinch the sides of the structure and release to recover the shape of the structure. The shape of magnetic field refers to the state transition-related information.

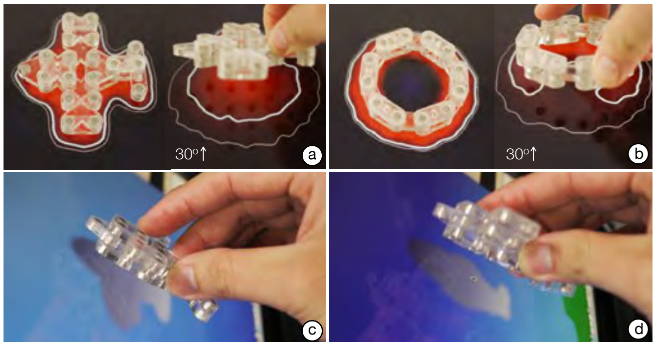

Figure 13. Rigid symmetrical constructions allow for near-surface interactions. (a) The plane model supports hover, rotation, and some directions of tilt. (b) The ring model supports hover and omni-directional tilting. (c) Flight simulation demonstrates that users can grasp a self-assembled magnetic airplane as a near-surface controller, such as (d) hovering and tilting to steer the airplane.

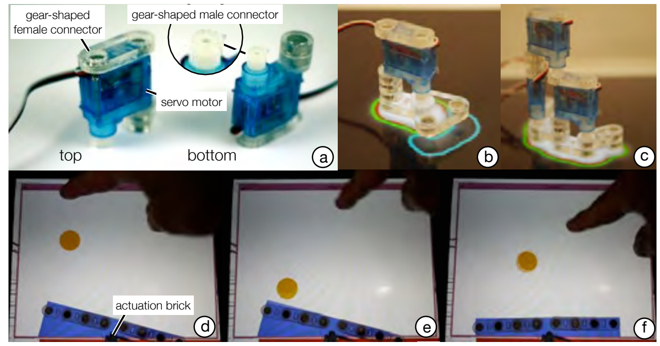

Figure 14. *Actuation bricks*. (a) The design of actuation bricks involves a tiny actuator. (b) The joint is bent by controlling the actuation bricks. (c) High degrees-of-freedom actuation is achieved using multiple actuation bricks. (d) Seesaw game. An actuation brick is used as the pivot of an assembled physical lever. (e) The falling ball bounces when colliding with the physical lever and, simultaneously, (f) the physical lever tilts.

Stretch: The X-serial structure (Figure 12d) that linearly connects many X-structures allows for 1D squeezing and stretching. Similar to manipulating a spring, users can squeeze or stretch the built structure in 1D. While inherited from the X-structure, the X-serial structure supports pinch operations to be performed on it. Since the magnetic field intensity increases when users push the magnets close to each other, the increased intensity refers to the pressure asserted by the users. This structure provides the maximum capability of stretching.

Squeeze: The V-closure structure (Figure 12e) that linearly connects many V-structures allows for free squeezing and stretching. Users can squeeze the boundaries to deform the closure structure and release to recover the shape of the structure, as if squeezing a stuffed toy. By extending from V-structure, the V-closure structure supports multi-pinch operation to be performed on it. Since the magnetic field intensity increases when users push the magnets close to each other, the increased intensity denotes the pressure asserted by users, and positions of where the increased intensity occurs indicate the positions and forces of pressures asserted by the users. This structure provides the maximum degrees of deformation.

Constructing Controllers for Near-Surface Interactions

Magnetic models can be detected above the display surface. By constructing symmetric models and locking the joints, such as the airplane model (Figure 13a) and the ring model (Figure 13b), the shapes of the magnetic field are symmetrical as well. The constructed rigid physical model thus provides 3D position and orientation information by the symmetrical magnetic field, and can function as tangible controllers for near-surface interactions.

In the tangible flight simulation (Figure 13c), users grasp his airplane assembly as the controller, tilt it in four directions to steer or pan in the context (Figure 13d), and lift or lower it to change the height of the flight naturally.

The physical construction provides users with just-in-time tangible affordances and immediate haptics to facilitate interactions. Inheriting the benefits of magnetic tangibles [15], the constructed models are free from hand occlusion, thus allowing users to freely grasp the models or to utilizing non-ferrous instruments in order to manipulate constructed models with a reliable detection.

EXTENDING GAUSSBRICKS FOR MORE INTERACTIVITY

In addition to introducing basic interaction techniques that exploit the features of magnetic fields and magnetic forces, this section further highlights several extensions by incorporating GaussBricks with shape-changing, sensing, as well as display methods to explore more interactivity in a wider context.

Enabling Shape-Changing Capability with Actuators

Applying actuators on a physical construction allows it to provide active force feedback. *Actuation bricks* (Figure 14a) apply the same brick design on tiny actuators, allowing users to easily snap actuators on the bricks. The servo motor used in the actuation brick is mounted with a gear-shaped male connector on its shaft. By snapping the actuation brick on a joint, the shaft interfaces with the female connector on the top of the brick, allowing for bending of the joint by controlling the servo motor (Figure 14b).

The seesaw game (Figure 14d) displays an example usage of the actuation bricks. Users construct the lever (in which an actuation brick is snapped as its pivot), place the lever on the display, and touch the display to drop a ball on one side of the lever. When the dropping ball contacts the lever, the ball bounces away (Figure 14e), and the lever tilts concurrently (Figure 14f), according to the torque in which the ball is exerted to the lever. The tilting lever may also hit other on-screen objects to bounce them up.

This application achieves a seamless physical-virtual interaction stage by using the mechanical responsive structure. Users can freely add actuation blocks and actuate the joints to create various movements (Fig. 14c). In addition to creating movements, different actuations can be considered such as changing the tightness of the joint by applying the brake motor, or simply turning on and off the motor. Tethers of the servo motors can be removed by using batteries, wireless connection, and tiny micro controllers. Notably, the form factor of the actuator can be made more compact if using lightweight actuators (e.g., shape memory alloys (SMA) or pneumatic actuators [31]).

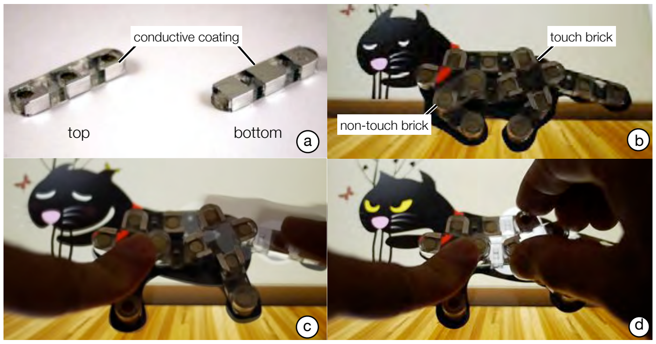

Figure 15. ***Touch bricks*****. (a) The design of actuation bricks involves conductive coatings. (b) A virtual pet application. The assembled cat model transfers the multitouch events of users to the underlying capacitive multitouch display. Non-touch bricks prevent the attached parts from unintentional input. (c) The cat is pleased by sliding fingers along its body. (c) The cat is irritated by pinching its body.**

Enabling Multitouch Inputs with Conductive Coating

The Hall-sensor grid can monitor the magnetic bricks independently. Therefore, on capacitive multitouch displays, additional input capabilities can be enabled by using the underlying touchscreen. *Touch bricks* (Figure 15a) that use conductive coating are applied on each magnetic joint independently. Stacking the bricks with joints forms a path that transfers the users touches from the surface of the construction to the touch screen at the same location. Since each joint senses touches independently, the construction that consists of many joints thus acts as a conductive matrix, capable of transferring multiple touch events to the underlying multitouch displays. Hence, user can perform multitouch gestures on the surface of the construction, as well as get sensed properly. Users can also avoid unintentional touch inputs by incorporating with general non-touch bricks.

A virtual pet application (Figure 15b) demonstrates the enabled touch input capability. Users use touch blocks and non-touch blocks to construct a sleeping cat. Users pat the cat to wake it up, please it by sliding their finger along its body (Figure 15c), and irritate it by pinching its body (Figure 15d). The cat's facial expression changes according to his feelings. While performing multitouch gestures on the cat's body, the users press the non-touch block to prevent the model from moving away.

This application demonstrates that integrating magnetic sensing and capacitive sensing can extend the input space of passive tangible objects. Applying indium tin oxide (ITO) coating on the touch blocks can maintain the transparency of the touch blocks [14]. The capability of supporting more subtle gestures (e.g., rubbing) can be achieved by incorporating the building bricks with a conductive 1D stripe or 2D matrix using Zebra rubber [6].

Enabling Display Capability with Fiber Optics

The building blocks are made of a transparent material, which already allows users to view the underlying graphical information through the construction. *Optic bricks* (Figure 16a) incorporates the building blocks with fiber optics bundle, further allowing the passive building blocks to display graphic-related information on the surface.

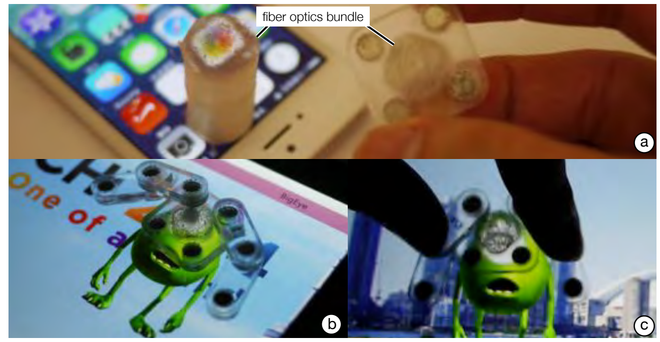

Figure 16. ***Optic bricks*****. (a) The design of optic bricks involves fiber optics bundled in the center of the bricks, which shifts the underlying display contents up to its surface. (b) A monster's eye is displayed on the optic bricks. (c) The monster is squeezed to change its eye expression.**

The monster puppet is constructed with an optic brick in the middle. The fiber optics bundle shifts the monster's eye from the underlying display up to its surface (Figure 16b). According to the monitored geometry of the construction, the monster's eye position follows its body position. When users squeeze the monster, the monster's eye changes to reveal his emotions (Figure 16c).

In addition to removing the visual parallax, incorporating fiber optics with GaussBricks provides a more direct approach for users to interact with physical models. More sensing and display functionalities can be developed by fabricating fiber optics using 3D printing technologies [5, 30].

CONCLUSION AND FUTURE WORK

This work has presented a novel magnetic building block system, GaussBricks, which enables real-time constructive tangible interactions on portable displays. A simple mechanical design of the magnetic building block is also introduced, as well a real-time sensing mechanism that enables configurable and stable form construction and manipulation on the portable displays as well as rich force feedback. Our results further demonstrate the feasibility of using advanced methods to enable wide applications using these building blocks, such as near-surface and multitouch interactions, as well as shape-changing and display capabilities.

Since the enabling features are essential to organic user interfaces [27], we recommend that future research extends the use of this material by creating prototypes for organic user interface design on commodity portable planar displays, which has widespread use and applications. Beyond educational and entertainment applications, the capabilities of rich-haptic, free form and real-time interactions provided by GaussBricks can also be useful for live performances. As Bricks [7] laid the foundations of graspable user interfaces, we sincerely hope researchers, developers and practitioners can apply the proposed platform and techniques to extend applications involving tangibles on interactive surfaces.

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