Magneto-Haptics: Embedding Magnetic Force Feedback for Physical Interactions

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ABSTRACT
We present magneto-haptics, a design approach of haptic sensations powered by the forces present among permanent magnets during active touch. Magnetic force has not been efficiently explored in haptic design because it is not intuitive and there is a lack of methods to associate or visualize magnetic force with haptic sensations, especially for complex magnetic patterns. To represent the haptic sensations of magnetic force intuitively, magneto-haptics formularizes haptic potential from the distribution of magnetic force along the path of motion. It provides a rapid way to compute the relationship between the magnetic phenomena and the haptic mechanism. Thus, we can convert a magnetic force distribution into a haptic sensation model, making the design of magnet-embedded haptic sensations more efficient. We demonstrate three applications of magneto-haptics through interactive interfaces and devices. We further verify our theory by evaluating some magneto-haptic designs through experiments.

CCS Concepts
•**Human-centered computing** → **Virtual reality;** *Haptic devices;*

Author Keywords
Magneto-haptics; magnetism; haptic feedback; permanent magnet; physical interaction.

INTRODUCTION
Haptic sensations and force feedback are important elements of the physical interfaces for computer devices, product designs, and rapid prototyping [8]. Researchers have applied haptic feedback on tablets through pen devices [11] and on interactive transparent display materials through static electricity [1] and electrical stimuli [3, 6], as well as on hardware [15, 18]. The augmentation of electronic devices with interactive physical interfaces is a burgeoning research area. Furthermore, it is desirable to build such interactivity without the utilization of a power supply, such as by using a power harvesting mechanism through user interaction [2]. Thus, we envision a future where more physical interactions are augmented and designed by building simple, useful, and non-electric physical mechanisms, rather than by combining multiple components of actuators and sensors. This capability would be a tremendous boon to the personal fabrication and rapid prototyping of interactive devices.

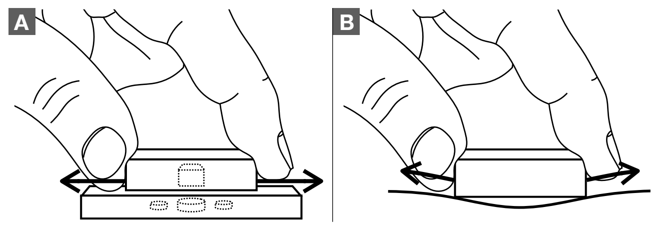

Figure 1. Example of Magneto-Haptics. (A) Three cylindrical magnets provide a magnetic force to the cube magnet. (B) This feedback creates a sensation as if one is moving an object on a gradient during active touch.

The use of magnetic force is a promising approach to realize physical interactions. Magnetic force provides a powerful force feedback and magnets can be easily embedded into objects. There were a few approaches proposed using magnetic force in actuation and personal fabrication. For actuation by a computer-controlled electromagnet, there are several types of electromagnetic haptic techniques. These include using magnetic levitation to design an applied haptics interface [5], floating a magnet in the air where users can touch it [7], as well as generating haptic feedback via the placement of magnets upon fingers [14] actuated by an array of electromagnets. For haptic sensations caused by the magnetic force, enhancing physical and tangible interfaces by adding and implanting magnets is gaining popularity [10, 15, 16, 18, 4].

FluxPaper [10] uses magnetized paper notes actuated from the backside of whiteboards to design and implement haptic experiences and self-actuation techniques. Magnetic plotter [16] designs the magnitude of the tactile sensation by rubbing magnetic sheets. Mechamagnets [18] show several patterns of physical interaction by a magnet. Moreover, bumping and hole illusion is observed using two magnets [4]. However, those works do not discuss the creation or design principles of haptic sensations. There have been very few studies that associate magnetic force feedback with haptic sensations in a systematic manner. One of the main reasons is that magnetic force feedback is non-intuitive, especially for the complex arrangements of magnets.

In this paper, we present *Magneto-Haptics*, a design approach of haptic sensations that associates haptic feedback with magnetic force. We explore a computational approach to express magnetic force feedback as a curve, termed *haptic potential*, so that one can understand and design haptic sensations using magnets more intuitively. Our approach not only simulates the magnetic force feedback embedded in interactive physical devices but also formularizes the relationship between magnetic force feedback and haptic sensations. We demonstrate its applications using a visualization tool, in building blocks, on interactive interfaces, and for alternative designs of mechanical components where the feeling and the experience of haptic sensations are enhanced by magneto-haptics. Furthermore, we validate magneto-haptics through experiments and discussions.

MAGNETO-HAPTICS

Magnets provide force feedback at proximity or when they are influenced by another magnetic field. When two magnets get close, they generate an attraction or a repulsion force, which is a well-known phenomena of electromagnetism and a commonly experienced sense, even for people who are not familiar with physics. Magnets with simple arrangements produce expectable force feedback. However, as magnetic force is inversely proportional to the square of the distance between two magnetic poles, it is difficult to properly model magnetic force feedback in applications involving physical interactions and tangible interfaces. This motivates us to develop a systematic way to simulate magnetic force feedback and map it into an actual tactile feedback so that it will be possible for anyone to design a non-electric mechanism of haptic feedback using only permanent magnets.

Magneto-haptics denotes the haptic and tactile feedback caused by magnetic force. We further define this term as a computational approach to express and simulate haptic sensations generated by magnets. Magneto-haptics provides an alternative visual and intuitive expression that we termed as haptic potential, meaning it can be felt as a curve (as in Figure 1), that illustrates the haptic sensation from permanent magnets during active touch. To distinguish the term from electromagnetic haptics [5, 7, 14], we select the word "magneto", which is a prefix specifically related to magnets. Magneto-haptics does the following:

- Allows for interactive editing in a three-dimensional space. The perceived force will correspond to the gradient of this potential (@fig:process).
- Simulates the distribution of magnetic force feedback of magnet-embedded movable objects given an arrangement of magnets and a moving path (@fig:process C).
- Formularizes the relationship between magnetic force feedback and haptic sensations. We refer to the resulting curve (as shown in Figure 2 C, D) as haptic potential – an intuitive representation of magnetic force feedback from the different arrangements of magnets.
- Permits the exploration of unique haptic potentials designed by permanent magnets that would otherwise be hard to discover (As the two different models illustrate in Figure 3).

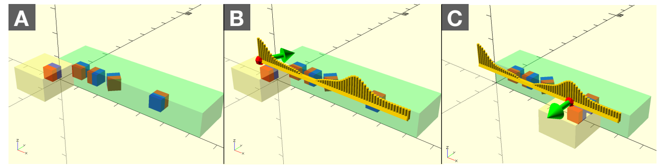

Figure 2. A design process is illustrated as (A) set active objects (in yellow), set fixed objects (in green), and insert magnets into these objects; (B) calculate the haptic potential (the yellow curve); and (C) animate the change of the magnetic force (represented by the green arrow) when an object is moved.

Furthermore, we developed a rapid calculation method that boosts the simulation speed 10 times using a general-purpose graphics processing unit (GPGPU) in contrast to the original calculation method using a CPU, allowing users to design and improve the haptic potential interactively. Using the techniques of magneto-haptics, users are able to design desired patterns of haptics using multiple permanent magnets. Users can check their results in simulation software and a visualization tool with three-dimensional (3D) graphics.

CALCULATION APPROACH

Traditional approaches use the analytical method of electromagnetism with an integral operation to estimate the force between magnets with simple arrangements. For example, there are general formulae for estimating the attraction and the repulsion force or the leaked flux density of a magnet or forces between two cylindrical magnets [13]. However, it is difficult to efficiently calculate precise force feedback among multiple magnets of different shapes at random placements, which requires complex mathematical models.

The dipole method [17] is a promising approximate calculation approach for analyzing the problem with complicated models of electromagnetism. This approach exhibits better computational stability compared to traditional approaches and has been successfully used in computer graphics for generating animation of a magnet's motion [12]. We improve the dipole method by permitting a near real-time, stable, and precise calculation of magnetic force feedback given complex magnet arrangements during active touch. The goal of our approach is to solve the actual physics problem of the magnetic force.

To determine the magnetic force feedback applied to the object along a moving path, our calculation algorithm involves the following steps:

- Step 1: We simplify the model of magnets by dividing them into two groups (a and b in Figure 4 A). We then split the magnets into cells of dipoles.
- Step 2: After converting each magnet into cells of dipoles, we use our modified dipole method to substitute the calculation of force between two magnets into the algebraic calculation for GPGPU (@fig:schematics C and D).
- Step 3: We formularize the relationship between magnetic force feedback and haptic sensations into haptic potential.

We now describe step 1 through step 3 in detail as follows with reference to Figure 4.

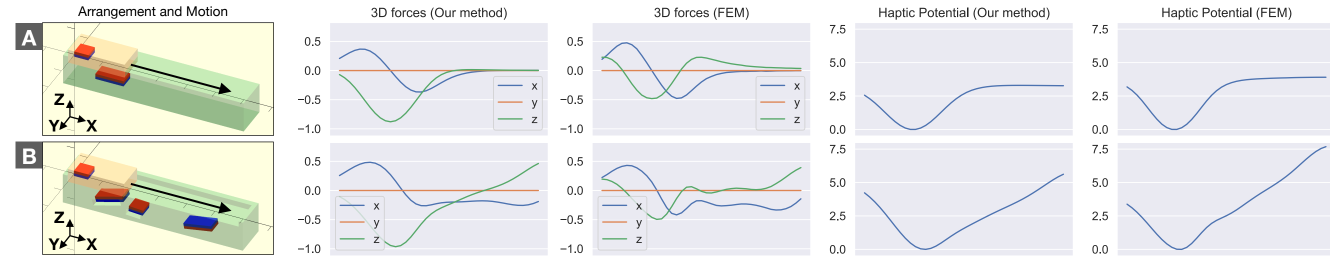

Figure 3. Examples of a simple model (A) and a complex model (B) with comparison of our approach and FEM approach. To compare with the simple model, the complex model is specially designed to provide linear curve of haptic potential. (Unit in force plot: N)

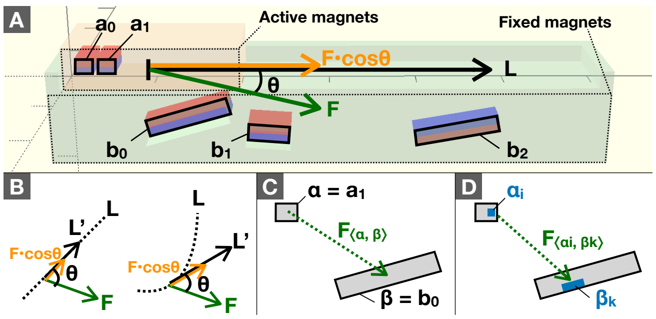

Figure 4. (A) Separate the magnets into active magnets and fixed magnets. Active magnets will move along a moving path L (B) Each pair of magnets (a1, b1) has force feedback. (C) Our approach performs force calculation at each cell of the dipole moment (m) of the magnet.

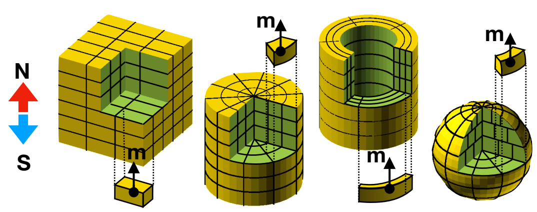

Figure 5. Simulation of cell splitting for four typical shapes of magnets (cube, cylinder, ring, and sphere). Each magnet is split into cells (i.e., 90). Each cell has a magnetic dipole moment (m), per its magnetization.

Step 1: Modeling and Splitting Magnets into Cells

Given a physical object embedded with several magnets (as in Figure 1 A), we divide those magnets into two groups, a group of active magnets (a_i) embedded in the rigid object that can be moved by the hand and a group of fixed magnets (b_i). To prepare for the calculation using the dipole method, we split and divide each magnet into cells of dipoles. We demonstrate this on four typical free-shape magnets as illustrated in Figure 5 by cutting along the original shape of the magnet. Each cell has a dipole moment m which turns toward the direction of the magnetic pole. As the sizes of the cells are essential factors for the precision of magnetic simulation, we determine the maximum splittable size of each cell according to the limitation of the dipole method. The dipole method demonstrates that the radius of the magnetic dipole is an essential factor for accuracy, as when the ratio of the radius R over the distance ρ between the two dipoles is less than 1/7, the plot accuracy is over 90%. Therefore, we determine magnet separation by constraining a magnet cell's maximum radius of dipole moment R to follow the following equation: $R < \rho/7$. In doing so, we guarantee the accuracy of the calculation. Although accuracy is guaranteed, the increased number of splits also increases the calculation cost proportionally. We therefore need to modify the dipole method to speed up the calculation to be near real time.

Step 2: Modified Dipole Method

We develop a modified dipole method for the efficient analysis of the magnetic force. According to Ampere's circuital law (@eq:ampere), a magnetic force F can be calculated from the magnitude of a magnetic dipole moment m and the spatial flux density B, where m is placed.

$$\boldsymbol{F} = \nabla(\boldsymbol{m} \cdot \boldsymbol{B}) \tag{1}$$

As shown in [12], to consider spatial flux density B at a certain position caused by a remote magnet, by splitting the remote magnet into N of dipole moments, spatial flux density B at a certain position caused by a remote magnet can be represented as a linear superposition of the individual dipole fields of the magnetic dipole moment m_i located at position r_i for $i = 1 \ldots N$:

$$\boldsymbol{B} = \frac{\mu_0}{4\pi} \sum_{i=1}^{N} \left[\frac{3\boldsymbol{n}_i(\boldsymbol{n}_i \cdot \boldsymbol{m}_i) - \boldsymbol{m}_i}{|\boldsymbol{r} - \boldsymbol{r}_i|^3} \right] \tag{2}$$

where μ_0 is the magnetic constant, $\boldsymbol{n}_i = (\boldsymbol{r} - \boldsymbol{r}_i)/|\boldsymbol{r} - \boldsymbol{r}_i|$ represents the distance between dipole moments.

The resulting force F_k acting on a magnetic dipole moment m_k located at position r_k after a differential operation with respect to r, can be represented as:

$$\boldsymbol{F}_k = \frac{\mu_0}{4\pi} \sum_{i=1}^{N} \frac{1}{|\boldsymbol{r}_k - \boldsymbol{r}_i|^4} \left[-15\boldsymbol{n}_{ik}((\boldsymbol{m}_k \cdot \boldsymbol{n}_{ik})(\boldsymbol{m}_i \cdot \boldsymbol{n}_{ik})) \right.$$
$$\left. +3\boldsymbol{n}_{ik}(\boldsymbol{m}_k \cdot \boldsymbol{m}_i) + 3(\boldsymbol{m}_k(\boldsymbol{m}_i \cdot \boldsymbol{n}_{ik}) + \boldsymbol{m}_i(\boldsymbol{m}_k \cdot \boldsymbol{n}_{ik}))\right] \tag{3}$$

The force F applied to an active magnet from dipole moments contained in a fixed magnet is the summation of all pairs of F_k.

$$\boldsymbol{F} = \sum \boldsymbol{F}_k \tag{4}$$

However, such a method requires a large number of separations of magnets to achieve precise results. This is computationally expensive. In addition, there is still an overhead of serial processing on the computer's CPU for each magnetic dipole moment m and distance r. To achieve near real-time performance to allow interactive editing, we improved this method by converting the dipole method into a linear algebraic formation, suitable for GPGPU.

Let

$$M_\alpha = (\, m_{\alpha_0} \quad m_{\alpha_1} \quad \dots) = (m_{\alpha_i})_{1<i<N_\alpha}$$
$$M_\beta = (\, m_{\beta_0} \quad m_{\beta_1} \quad \dots) = (m_{\beta_k})_{1<k<N_\beta} \quad (5)$$

representing sets of magnetic dipole moments for an active magnet (as α) and a fixed magnet (as β) in matrix form.

$$R = \begin{pmatrix} \hat{r}_{00} & \hat{r}_{01} & \dots & \hat{r}_{0k} \\ \hat{r}_{10} & \hat{r}_{11} & \dots & \hat{r}_{1k} \\ \vdots & \vdots & & \vdots \\ \hat{r}_{i0} & \hat{r}_{i1} & \dots & \hat{r}_{ik} \end{pmatrix} = (\hat{r}_{ik})_{\substack{1<i<N_\alpha \\ 1<k<N_\beta}} \quad (6)$$

representing sets of distances between each pair of dipoles in matrix form, where $\hat{r}_{ik} = (r_{\beta_k} - r_{\alpha_i})/|r_{\beta_k} - r_{\alpha_i}|$.

Let

$$X = 3M_\alpha \cdot \langle M_\beta, R\rangle + 3M_\beta \cdot \langle M_\alpha, R\rangle + 3R \cdot \langle M_\beta, M_\alpha\rangle - 15R(\langle M_\beta, R\rangle\langle M_\alpha, R\rangle)$$

where M_α and M_β are sets of dipole moments. We can transform Equation 3 into

$$F_{\alpha\beta} = \frac{\mu_0}{4\pi} \sum_{i,k}^{N_\alpha, N_\beta} \frac{(X)_{ik}}{|r_{\beta_k} - r_{\alpha_i}|^4} \quad (7)$$

where N_α, N_β are the total number of separatable dipoles from active and fixed magnets α and β. $F_{\alpha\beta}$ means the force applied to an active magnet α from a fixed magnet β. Finally, the total force feedback F_T applied to the set of all active magnets (as $a_0, a_1, \dots$) from fixed magnets (as $b_0, b_1, \dots$) can be calculated in Equation 8 by summing up N_a numbers of active magnets and N_b number of fixed magnets:

$$F_T = \sum F_{\alpha\beta} = F_{a_0 b_0} + F_{a_0 b_1} + \dots + F_{a_{N_a} b_{N_b}} \quad (8)$$

where $_T$ means the total force from each pair of magnets (in which one is an active magnet, and the other is a fixed magnet). Thus, F_T is also force feedback applied to a rigid object that contains some magnets to be touched by hand. Note that F_T results in a series of vectors of force at each point along the path L. This approach provides near real-time calculation efficiency while still preserving the accuracy.

Step 3: Formalization of Magneto-Haptics

The series of the magnetic force F_T calculated in Equation 8 represent the distribution of the magnetic forces applied to the active magnets from fixed magnets along a moving path L (as shown in Figure 4). While F_T is a summation of forces along three axes, a direct plot of F_T does not match the actual haptic sensation. Thus, we introduce a new formula to convert magnetic force into haptic sensations. We treat this as a physics problem, in which work can be calculated as the total force required to move an object. We hypothesize that the haptic feedback can be represented as the work W done by the finger. We convert the distribution of the magnetic force F as the "haptic potential" with an integral operation.

$$W = \int F_T \cdot dx \quad (9)$$

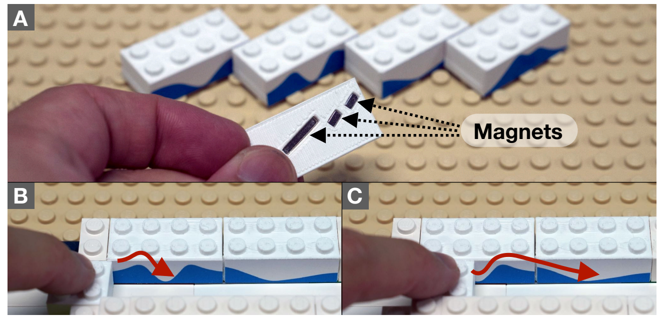

Figure 6. LEGO blocks embedded with various shapes of magneto-haptics (top) with corresponding haptic potential curves labeled on the side (bottom). Users can explore new combinations of haptic sensation.

The finger can move the active magnets along a moving path L. As each vector has three-dimensional direction, θ can be represented as an angle between two vectors (As illustrated in Figure 4 B). In each time step, we calculate θ that represents the angle between F and L, meaning the vector direction of path at a certain point.

Thus, the force at each point along a path L can be calculated according to the vector direction. Consequently, we formularize magneto-haptics into the following mathematical representation:

$$P = \int |F_T| \cdot \cos\theta \cdot dL \quad (10)$$

Through this approach, we are able to visualize the haptic potential using a single curve (as shown in Figure 3).

APPLICATIONS

Visualization and User Procedure

The users can make interactive tools while designing magneto-haptics. For example, we developed a simulation tool and a visualization tool. The users of these tools need only to prepare (1) a 3D model file of objects they design, (2) a JSON file that contains parameters of the magnets (position, rotation, and size), and (3) a moving path defined by sets of angles θ. The haptic potential was calculated by the simulation tool (a python module) and was displayed on the visualization tool (as shown in Figure 3). The users of the software applications can interactively update their arrangements of magnets in the objects using the visualization tool. Our tool displayed the haptic potential in real time. The visualization tool uses a GUI-based open-source CAD software called OpenSCAD. After the design is finalized, OpenSCAD converts the model into the STL data format (a common format for 3D printers). The users of these tools can then print the object and embed magnets for creating their applications.

Magneto-Haptics in Building Blocks

Using LEGO®blocks, users can build physical objects with ease. Researchers have been using LEGO blocks instead of 3D printed materials for fast prototyping [9]. The functionality of LEGO blocks also allows for the reconfiguration of physical objects. Thus, we adopt LEGO blocks and embed magnets inside the blocks for creating special magneto-haptics. To

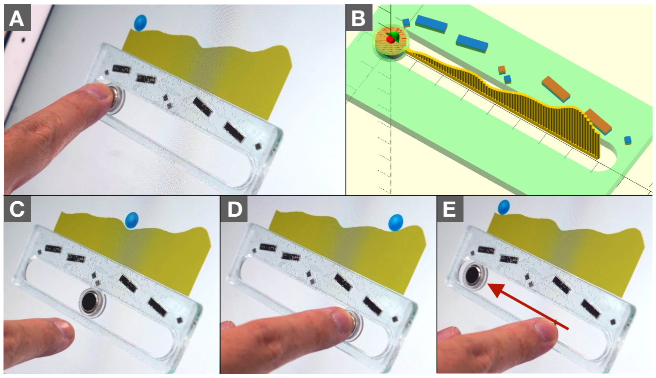

Figure 7. Example application of enhancing an interactive interface by magneto-haptics: (A and C through E) the iPad touch interface is enhanced by a magnet-embedded acrylic board. (B) The simulation result from the visualization tool.

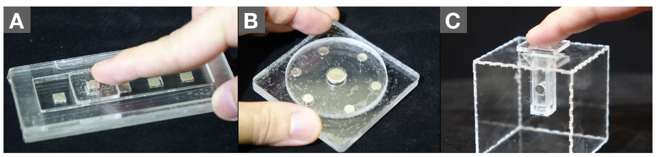

Figure 8. Example designs of physical interfaces embedded with magnets: (a) slider, (b) dial, and (c) push button.

implant magnets into plastic blocks, one first needs to design holes for the magnets. We developed a supporting tool that can automatically cut an appropriate hole through the 3D model of blocks. We then labeled each block with corresponding haptic potential curves (@fig:legos, the blue graph) obtained from our algorithm. Using magneto-haptics, users are able to distinguish and design haptics scenarios with several configurations in building blocks.

Magneto-Haptics for Enhancing Interactive Interfaces

We explored the use of magneto-haptics by enhancing tablet interfaces. Tablet computers are among the most popular user interface (UI) devices as users can intuitively manipulate the interface by touching or using a stylus. We designed an interactive game interface on an iPad, whose touch interface was enhanced by a magnet-embedded object (@fig:interactive). We first designed the hardware using transparent plastic (an acrylic) because it is easy to cut and build. We then implemented an interactive application (i.e., a ball climbing game) and displayed its visual effect (i.e., the ball follows the trajectory of the finger movement and falls down when the finger is removed) associated with the users' active touches on the hardware. Magneto-haptics was able to precisely model the trajectory of the visual effect according to haptic sensation.

Magneto-Haptics for Alternating Physical Components

Touching and grabbing movable objects with the hands is an essential action for a physical interface. However, most results from rapid prototyping lack aspects of haptics. Compared to other mechanical approaches, embedding magnets into objects is a powerful method. As it does not only present force feedback but also alternates the mechanics, we demonstrated the possibility of developing physical objects with movable parts that provide tangible feedback via magneto-haptics. We

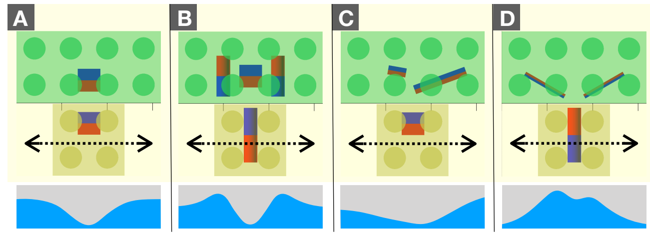

Figure 9. Patterns of haptic potentials of magneto-haptics (the blue graph with curves on the bottom), each corresponding to a design of a magnet-embedded device (top, using cubic and cylindrical magnets).

designed physical interfaces by estimating and simulating their haptic feedbacks using magneto-haptics. In Figure 8, we demonstrated three patterns of alternative mechanisms that we designed using only magnets. The haptic device can be created by designing its haptic magnitude and scenario.

EXPERIMENT

Experiment Setup

We conducted two experiments to demonstrate the haptic capability of magneto-haptics as well as to validate the haptic potential. We designed four different patterns of magneto-haptic devices with LEGO-shaped blocks, as shown in Figure 9. Each device was created such that the subjects were able to pinch a small yellow block and move it horizontally next to a green block. To prevent users from anticipating the mechanism and its haptic feedback from its appearance, we ensured that the embedded magnets were hidden inside each device and thus were not visible. The devices were fixed on a LEGO board with other LEGO blocks. We recruited a total of 9 people to participate. The average age of the subjects was 35.6 years.

Experiment 1: Distinction Test

This experiment aims to test if different patterns of haptic potentials modeled by our method are distinguishable from each other. First, we asked the participants to touch and feel these four magneto-haptics devices one by one given sufficient time. They were informed that each device has a different pattern of haptics, designed with magnets. The participants were presented with four curved graphs of haptic potential (as the blue graph in Figure 9) and four magneto-haptic devices labeled in a randomized order (1 to 4). They were asked to match each graph to a magneto-haptic device. They were given sufficient time to read each graph and touch each device before submitting their answers. Four curved graphs and the number (1 to 4) of the devices were printed on a sheet of paper. They were asked to draw lines to connect a graph with a number corresponding to the devices to show their matching results.

Experiment 2: Sensibility Test

This experiment aims to measure the sensation levels of the magneto-haptic devices. Similar to experiment 1, after the touch period of each device, the participants were asked to rate the sensitivity of the haptic sensations on a questionnaire printed on a sheet of paper. The sensitivity was divided into

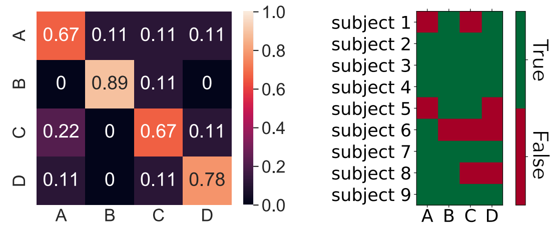

Figure 10. Results of the distinction test in a confusion matrix.

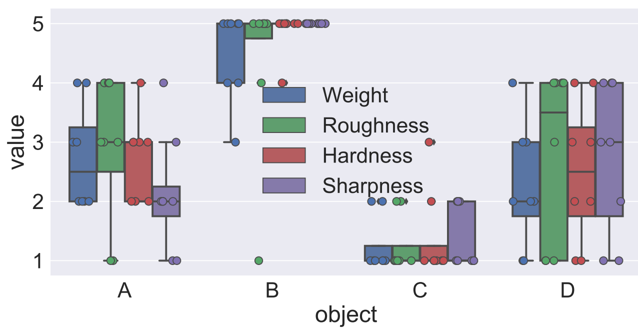

Figure 11. Results of the sensitivity test. The horizontal axis represents four object types, and the vertical axis represents the 5-scale value of the questionnaire.

four categories: "lightness vs. weight", "smoothness vs. roughness", "softness vs. hardness", and "flatness vs. sharpness". For each category, they were asked to rate each sensitivity on a scale of 1 to 5.

Results

The percentage of correct answers from experiment 1 is shown in Figure 10. The percentage of the subjects who are able to successfully match the device and haptic potential for device A through D are 67%, 89%, 67%, and 78%, respectively, and no one submitted wrong answers to all selections. The results of experiment 2 are plotted in Figure 11. Although within each device, the ratings of the sensation level for the four categories do not differ much, each device has a different trend from others. By observing the haptic potential graph of each device in Figure 9, we observed a correlation between the sensation level (As in Figure 11) and the shape of the haptic potential curve. For example, devices A and C have similar shapes in haptic potential; thus, they are easy to be mistaken. Meanwhile, striking shapes, such as those of device B are easy to be distinguished from others. When cross-correlating the distinction and the sensitivity test, we observed that although in experiment 1, devices A and C can be confused, in experiment 2, the levels of sensitivity of devices A and C are reported to be different. Thus, it has been demonstrated that magneto-haptics enables the design and creation of distinguishable haptic sensations. Furthermore, our method enables users to make unique and significant sensations using magnets.

DISCUSSION

Magneto-Haptics and its Usability

From the two experiments conducted, we observed that the differences between each pattern of magneto-haptics are easily distinguishable, and the haptic potential matches what the users actually feel. Thus, using our approach (the modified dipole method with GPGPU acceleration), it is possible to design magneto-haptics to achieve the targeted and desired patterns of sensation in near real time. Additionally, we received comments from one of the haptics researchers who reported that although the haptic sensation using magnets is not new because of [4], it has never been created with magnets. Thus, our approach associates a novel relationship between human sensation and magnetic force.

Simulation method

There are two major simulation methods for electromagnetism: the finite element method (FEM) and the dipole approximate method. The method we selected is the dipole approximation method, which treats magnetic cells as chunks of small dipoles. Thus, when simulating the normal sizes of magnets, we must split them into 3D cells and sum the force and torque values among the cells. The reason we did not adopt the FEM is that it requires too much time and precision for split alignments. If we were to simulate the magnetic force of a cylinder or a cube magnet, we would have to generate splittable cells along the surface of the magnet shapes. In addition, although the accuracy of dipole method is not such high, the haptic curves can ignore minimum differences between FEM and dipole method (as shown in Figure 3). Thus, the dipole approximation method is easier to use and can handle different magnet shapes, making the design more flexible.

Limitation on design tools

As our focus was on building theory and a minimal UI as a visualization tool, we did not build a new GUI program to allow users to design in three dimensions. Considering that a rich design tool is helpful for users, we leveraged 3D CAD software. We did, however, develop a GUI visual simulator to test the validity of our method and check its correspondence to the actual results of magneto-haptics from physical simulations. However, as the visual simulator was not an essential part of this study, we have not described it in detail.

CONCLUSION

In this paper, we proposed magneto-haptics, a new approach for designing and building haptic feedback powered by magnetic forces, as applied from other magnets, during the users' active touch. To understand and convert the incalculable physical phenomena into calculable haptics sensations, we leveraged electromagnetism by converting the typical dipole method into an algebraic formula for rapid processing. We derived haptic potential from magnetic force formulae for a new theory of magneto-haptics. We also applied magneto-haptics to physical interactions, including interfaces and devices. Through application demonstrations and experiments, we verified the capability and scalability of magneto-haptics.

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