Magnetic Plotter: A Macrotexture Design Method Using Magnetic Rubber Sheets

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ABSTRACT

This paper presents a method for designing tactile macrotextures with magnetic rubber sheets. In the method, named “Magnetic Plotter”, a desktop digital plotting machine combined with a tiny neodymium magnet writes fine magnetic patterns on the surface of the magnetic rubber sheets. This method enables users to design magnetic fields freely with inexpensive commercially available materials as if they are drawing pictures. Moreover, when the magnetic sheets are rubbed together, unique haptic stimuli are displayed on the fingers. The haptic stimuli can be changed by the magnetic patterns designed on the rubber sheets. We developed a prototype of the Magnetic Plotter and investigated the range of the generated haptic stimuli and the texture design possibilities.

Author Keywords

Magnets; DIY; haptic; tactile; rapid prototyping; interactive devices; digital fabrication; home.

ACM Classification Keywords

H.5.m. Information interfaces and presentation (e.g., HCI): Miscellaneous;

INTRODUCTION

Digital fabrication tools are becoming more popular. Desktop 3D printers and hobby cutting machines empower people who have an idea, imagination, and creativity, i.e., the Makers [1]. Nowadays, people can make many kinds of things even if they do not have technical knowledge or experience.

As a consequence, a major challenge in human-computer interaction (HCI) has been to find ways to give a particular functional capability to those objects with a computational aid. To date, a broad range of functional capabilities have been achieved with digital fabrication tools. For example, physical parameters, such as color, hardness, or elasticity, can be changed by the forming material or printing method [2-5]. Moreover, shape-changing, electrical, acoustic, and optical functions have been achieved in various ways [6-10]. However, there seems to be room for improvement in the prototyping of magnetic functions.

Magnetic forces have been used in various interactive techniques, especially in tangible and tactile interfaces [11-22]. This is because permanent magnets are simple and convenient elements that can generate strong attraction/repulsion forces without energy, while and electric magnets are very useful actuators with dynamic controllability. Moreover, magnetic forces can pass through most everyday materials, such as paper, cloth, wood, and plastic. Therefore, magnets are also proper elements for home fabrication and rapid prototyping.

However, it has been difficult to construct magnetic displays or editable magnetic fields as a DIY (do it yourself) project. Permanent magnets cannot change their polarity instantly, and electric magnets require long coils and huge currents to generate strong magnetic fields. As a solution, we present Magnetic Plotter, a home-use magnetic field editing system for haptic interaction.

Magnetic Plotter is a new method for designing magnetic functions. It uses thin magnetic rubber sheets as media for magnetic fields. A desktop-sized plotter with a tiny neodymium magnet can write and rewrite magnetic fields on the surface of the sheets. In addition, just a pair of magnetic-plotted rubber sheets can provide unique haptic textures when they are rubbed together (Figure 1). The system does not require any soldering, programming, or heavy equipment.

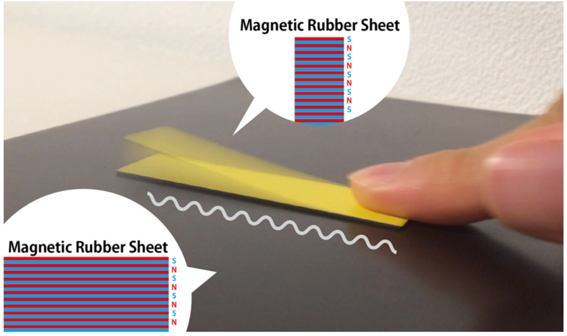

Figure 1. Magnetic Plotter can plot precise magnetic polarities on magnetic rubber sheets, and the magnetic sheets can display unique haptic stimuli on the surface of the sheet.

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The main contributions of this research are as follows:

- A demonstration of the concept of rewritable magnetic-field designs utilizing magnetic rubber sheets and a neodymium magnet.
- The establishment of a method for designing particular haptic surfaces on the magnetic sheets.
- Implementation of the whole system using commercialized materials, equipment, and software.

RELATED WORK

HCI research has produced several gadgets with magnetic functions. For example, magnet-embedded blocks have been used as interactive tangible objects in many ways [11-14]. The blocks can be connected to and separated from each other easily [11]. They can also indicate proper connection directions by utilizing the attraction and repulsion of magnets [12]. Moreover, a magnetic sensor array can estimate the positions and orientations of the magnet-embedded blocks [13], and an electric magnet array can actuate magnet-embedded gadgets [14].

These magnetic approaches are not limited to tangible blocks. A magnetic force applied to iron powder or magnetorheological (MR) fluid will radically alter their behavior [15]. MudPad [16] is a touch display with an MR pouch layer and an electromagnetic layer within its surface. It can change its elasticity selectively and locally by actuating electromagnets, which, in turn, can change tactile sensations and provide different haptic feedback.

Regarding interactivity and haptic feedback, a simple approach is to just attach a magnet to a finger. A tiny magnet attached to a finger nail turns a finger into an interactive interface [17, 18]. In addition, a tiny magnet mounted on a finger pad can be a part of a force-feedback haptic interface [19, 20]. When the magnet reacts to the magnetic field around it, the finger pad will deform as if it were making contact with a real physical object.

However, while attaching a magnet to a finger is simple, the magnetic display is still complex. An electromagnet array requires a current control processor, complicated wiring, high-voltage electricity, and a number of coils, and the strength of the magnetic field of an electromagnet depends on the size of the coils and the electrical current. In addition, there are still technical barriers to constructing an electromagnetic array.

Meanwhile, other methods that simply use permanent magnets to construct a magnetic haptic surface have been proposed. Bump Ahead [21] is an interactive haptic interface that does not use an electromagnet for the generation of haptic textures. The interface can provide strong haptic stimuli to the hand through a handheld device. When the handheld device is slid over another magnetic array, the user's hand feels the sensation of physical bumps. Moreover, the system can switch its haptic sensation on and off by rotating the magnet array embedded in the handheld device. This haptic surface does not require any soldering, lines, or electricity. This method is a kind of DIY haptic, which is very well suited for prototyping or workshops.

The haptic sensation varies depending on the arrangement of the magnet array beneath the handheld device. However, it is hard to re-arrange the magnets because they are fixed in a way that prevents them from attracting each other. This makes re-designing the haptic sensation difficult. Another issue is that the resolution of the magnetic field is restricted by the size of the magnets.

Polymagnet [22], a magnetic product company, has developed a technology for computational magnetization of permanent magnets [23]. It can magnetize neodymium magnets in such a way as to "print the polarities". The magnets with a printed special pattern of polarity are applied to their products like no-spring springs, no-abrasion latches, and twist-release connectors. FluxPaper [24] is a system that creates an ultra-thin magnetic layer (0.1 mm) on a sheet of paper using neodymium powder and resin. When magnetized using a laboratory-level magnetizer, the neodymium layer exhibits magnetic attraction and repulsion, and a thin sheet of paper can be used as a magnetic medium.

These magnetic objects can present an arbitrarily shaped magnetic field without wiring or an energy source. However, a very high magnetic flux density is required to magnetize the neodymium magnet. The maximum magnetic flux density of FluxPaper's magnetizer is over 3000 mT, and the magnetic attractive force between the neodymium magnets in the magnetizer (20 mm in diameter and 20 mm in height x 2) reaches 5~10 kg. If the magnets attract each other, the fingers could be injured. Further, such a high magnetic flux density could ruin a magnetic storage medium like a hard disc drive. Therefore, such a strong magnetizer has to be handled with care and is not suitable for personal use.

Thus, we propose Magnetic Plotter as a solution for easy-to-design magnetic functions at home. The ferrite magnetic rubber sheets used in this research have a weaker magnetic force than neodymium magnets. Nevertheless, we found that they can be fully used as a "tactile display" at the personal fabricating level. The design method uses only a tiny neodymium magnet for the magnetization. Hence, the custom design of magnetic fields can be done even at home.

Using the developed prototype, we established a method for printing the magnetic polarities. We also explored the kinds of haptic applications that can be designed by utilizing Magnetic Plotter. Through this study, we aim to provide users with the ability to fabricate and prototype magnetic functions using inexpensive materials.

CONSTRUCTION OF MAGNETIC PLOTTER

Magnetic Plotter is a straightforward system for designing magnetic polarity. It comprises just three parts: a magnetic rubber sheet, a neodymium magnet, and a personal digital cutting machine. A tiny neodymium magnet placed at the top of the plotting head of the cutting machine magnetizes the magnetic rubber sheet exactly as designed. Creators can describe magnetic fields freely and make several kinds of unique textures on the magnetic sheets.

Though bringing out the system's performance requires careful selections and settings, the system design is so simple that even a person with no experience in hardware design can create original magnetic patterned sheets easily.

Magnetic Rubber Sheet

The magnetic rubber sheet for Magnetic Plotter is commonly used as stickers for cars, refrigerators, and whiteboards. Magnetic rubber is a molded rubber product made from a mixture of ferrite powder and rubber. When it is molded into a 1-mm-thick sheet, it is soft and flexible and easy to cut with scissors.

In selecting of the magnetic medium of Magnetic Plotter, we sampled four types of magnetic rubber sheets (Figure 2). Sample 1 is a very thin printable magnetic sheet (MagX Co., Ltd., MSPG-03-A4-1). Samples 2 and 3 are low-priced products that can be purchased at a dollar store. Sample 4 was purchased directly from the manufacturer (Magfine Co., Ltd., RM10). All samples are magnetized with stripes of north-south poles. We measured the thickness of the magnetic layer and the pitch of the pole stripes by visualizing the magnetic patterns with a magnetic field viewer sheet (Simotech Co., Ltd., MV0010-C01). We also measured the surface magnetic flux density (***Bs***) of the samples. We scanned the center area (10 mm x 10 mm) of each test piece at intervals of 1 mm using a Gauss meter (Kanetech Co., Ltd., TM-801) and recorded the maximum values. Table 1 shows the measurement results.

On the basis of the measurement results, we selected sample 3 as the medium for Magnetic Plotter for its availability and processability, which are important for a home-use magnetic design system. In addition, sample 3's surface magnetic flux density makes it acceptable as a magnetic medium.

No	Thickness [mm]	Pole Pitch [mm]	Max *Bs* [mT]	Price [US$/100cm^2]
1	0.10	2.25	9.3	0.37
2	0.55	3.00	29.2	0.36
3	0.70	2.00	31.5	0.17
4	1.00	2.00	48.9	0.82

Table 1. Specifications of the samples of magnetic rubber sheet.

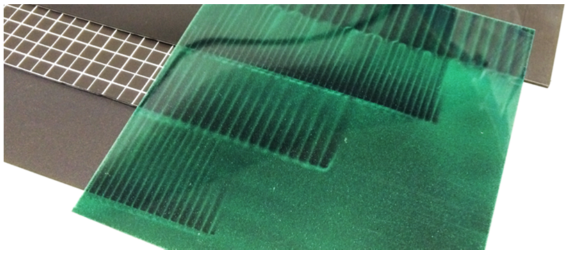


Figure 2. Sample pieces of magnet sheet with visualization of magnetized pattern.

Magnetization of Magnetic Rubber Sheet

When a strong magnetic field is applied to magnetic substances, the atomic dipoles align with the magnetic field, and the alignment will remain even after it is removed. This magnetization is the fundamental principle of a magnetic substance. Magnetic storage media, such as videotapes and hard disc drives, work on the same principle. Similarly, a magnetic rubber sheet can record the magnetic polarity.

Typical specifications for a ferrite rubber magnetic sheet are (working temperature ≦80 ℃) [25] residual magnetic flux density (***Br***) of 160~190 mT, coercive force (**Hcb**) of 100~119 kA/m, intrinsic coercive force (**Hcj**) of 143~199 kA/m, and relative permeability (μ/μ_0) of 1.1. From the specifications, we estimated the intensity of the magnetic field required for the magnetization of a 0.8-mm-thick ferrite rubber sheet.

According to the demagnetization curve [26], the required intensity is 220 kA/m or more. We transformed the required magnetic field into the magnetic flux density using the relative magnetic permeability and the permeability constant (μ_0=4π×10^-7). As a result, the derived intensity of the magnetic flux density is 304.1 mT. Touching a magnet with 304.1 mT or more to a magnetic sheet changes the polarity of the surface of the sheet.

Neodymium Magnet

The surface magnetic flux density of a neodymium magnet varies according to its shape. For the magnetic resolution of the plotting system, the plotting head should be as small as possible.

Figure 3 shows the surface magnetic flux density of neodymium magnets with different shapes, generated from the database of a magnet company [27]. When neodymium magnetic material is molded into a 1-mm-diameter cylindrical shape, the surface magnetic flux density is less than 220 mT even if the length is more than 10 mm. However, when it is molded into a 2-mm diameter, the surface magnetic flux density (***Bs***) exceeds 300 mT even if the length is 2 mm. Thus, we used a neodymium magnet with a 2-mm diameter and 10-mm length (***B***: 372 mT). The price is approximately 0.34 US$ per magnet.

Plotting Machine

The plotting machine we use is Craft Robo CC330 (Graphtech. Inc.) (Figure 4), which is one of the most popular commercialized home-use cutting machines. It can cut thin materials up to in the size of A4 (297 mm x 210 mm). Two stepper motors in the plotter machine are controlled independently to move the plotting head and feed the medium material, and a solenoid in the plotting head can move it up and down. The minimum controllable size of the stepper motor is 0.05 mm.

For magnetic plotting use, we removed the cutting blade in the plotting head. The diameter of the blade is 2 mm; therefore, it is easy to insert the 2-mm-diameter neodymium magnet into the hole of the plotting head (Figure 5). To affix the magnet, simple taping is enough; therefore, a special spacer or a new head is not required.

The plotting file can be designed by drawing software like Adobe® Illustrator. Plug-ins for Adobe® Illustrator that can convert the drawn lines into the plotting signal have been distributed by the plotting machine company [28]. Thus, designers can create files in as if they are drawing pictures, without coding programs. The file can be saved in the portable document format (pdf), so it is easy to copy, re-edit, and share.

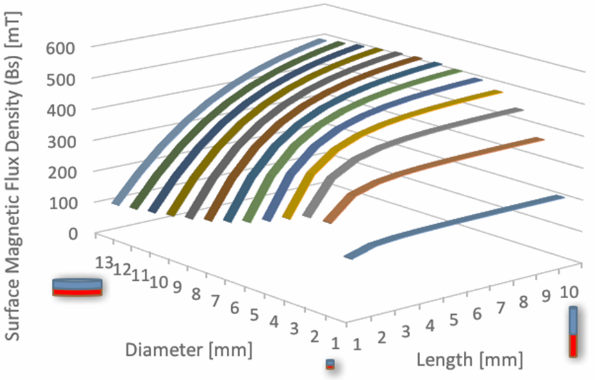


Figure 3. Surface magnetic flux density of cylindrical neodymium magnets.

Figure 4. Plotting machine, Craft Robo CC330.

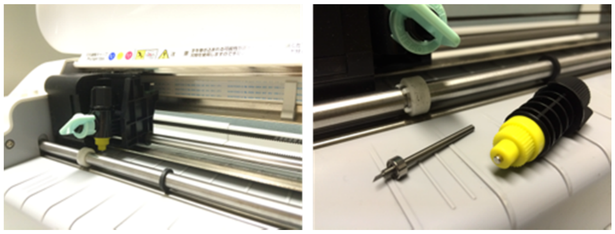


Figure 5. The original blade and the neodymium magnet mounted on the tip of the plotting head.

PLOTTING

Plotting procedure

Basically, the plotting procedure is as follow:

1. Design: Prepare a plotting file by using drawing software.
2. Setup: Connect the plotter to the computer, set a magnetic sheet into the plotter, and install a neodymium magnet into the header of the plotter with the S-pole side down.
3. Plot: Send the file and run the plotter to write the magnetic designs for the S-pole.
4. Change the pole: Change the direction of the magnet and set it again with the N-pole side down.
5. Plot: Run the file and plot the design for the N-pole.
6. Complete: If something needs to be revised, return to 1.

Linear Drawing or Pointillistic Plotting

We examined whether the surface magnetic flux density differs depending on how the magnetic pattern is plotted. Though the plotter can draw lines based on vector data, sliding a magnet on the surface of the magnetic rubber sheet cannot align the orientation of the atomic dipoles with perfect verticality, and, as a result, the surface magnetic flux density decreases. Plotting in a pointillistic manner can make the orientation of the dipoles more vertical, but it consumes more time than the sliding approach. Therefore, we prepared three test pieces of magnetic rubber sheets, with which we plotted the same pattern in three ways.

The magnetic pattern was a 2-mm-pitch stripe of S-poles and N-poles with the length of 30 mm and width of 22 mm. The stripes were plotted dotting with 2-mm intervals, dotting with 1-mm intervals, and drawing 11 lines. We measured the surface magnetic flux density of the middle area (6 mm x 6 mm) at intervals of 1 mm using the Gauss meter. Table 2 shows the number of steps, processing time, maximum/minimum values of the surface magnetic flux density. According to Table 2, although the maximum surface magnetic flux densities are slightly lower than they were at the time of purchase (about 30 mT), there are no large differences between the three methods, in spite of the large difference in the number of steps and plotting time.

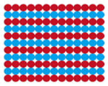
● 2-mm-diameter N-pole ● 2-mm-diameter S-pole		Steps	Processing time [sec]	*Bs* [mT]
	2-mm interval dots	176	57.0	Max: 28.6 min: 6.7
	1-mm interval dots	352	96.4	Max: 24.1 min: 18.7
	lines	11	8.3	Max: 25.5 min: 22.3

Table 2. Specifications of the samples of magnetic rubber sheet

Meanwhile, the minimum surface magnetic flux density values differed with the plotting method. The shape of the magnetic field of the 2-mm-interval dots had an uneven shape; therefore, the surface magnetic flux density varies varied with the point of the measurement. On the other hand, the uniform magnetic fields of the line method exhibited a constant value of surface magnetic flux density.

From these results, considering the time for processing and the uniformity of the magnetic field, we concluded that the magnetic fields should be written in a linear manner. In addition, when drawing a broad area with one pole, filling the area by plotting 1-mm-interval lines is the better way to make a uniform magnetic field.

TEXTURE DESIGN

Using the above-mentioned configuration and procedure, we prepared several magnetized pieces. With the test pieces, the two magnetic sheets generated a kind of haptic stimuli when they were rubbed together: a texture-like haptic was generated, as if there was a bumpy plane between the two magnetic sheets, although the two sheets were not vibrating in the perpendicular direction.

This phenomenon is called a lateral-force-based haptic illusion [29]. Robles-De-La-Torre et al. described this phenomenon in their paper "Force can overcome object geometry in the perception of shape through active touch" [30]. According to the paper, when a shear force cue of a bump is displayed on a finger pad, the subject feels as if there is a rigid bump even though there is a hole geometry. In addition, Saga developed an interactive haptic display based on this phenomenon [31]. Moreover, Fujii et al. [32] elucidated this phenomenon utilizing the shear force generated by magnets.

According to these studies, the haptic sensation of the two magnetic sheets is due to the magnetic force between them. For this reason, it is assumed that the haptic texture can be controlled by the shape of the magnetic fields of the magnetic sheets. Thus, we tried to control the texture by designing their shape with Magnetic Plotter.

The minimum designable size of the magnetic field depends on the size of the neodymium magnet (2-mm diameter) and the accuracy of the plotter. With the configuration described above, the size of the bumpy texture is between 2 and 10 mm. A texture of this size is classified as a macrotexture according to the definitions of pavement texture [33].

Spatial Frequency Design

Rubbing two 2-mm-pole-pitch magnetic sheets together displayed strong haptic stimuli with a corrugated shape and a 4-mm wavelength. Similarly, corrugated shapes with 8- and 16-mm wavelengths were displayed with 4- and 8-mm-pole-pitch magnetic sheets (Figure 6), though the intensity of the macrotexture decreased with decreasing spatial frequency.

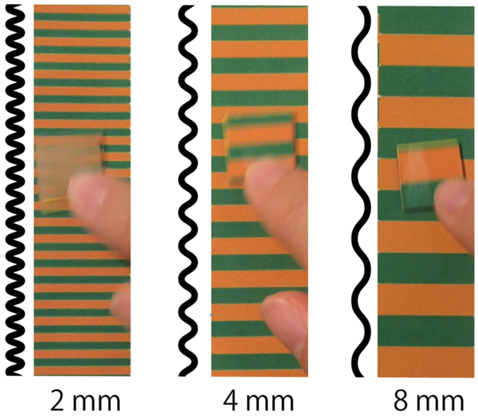


Figure 6. Difference in the spatial frequency of the texture with different magnetic pole pitches.

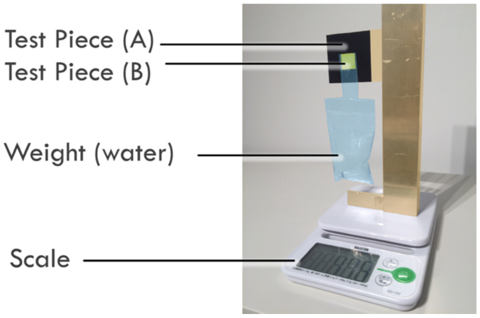


Figure 7. Instrument for measuring holding force.

When the two magnetic sheets stick to each other with attractive force, a shear force will be required to move them. To investigate the magnetic holding force between the magnetic sheets, we prepared test pieces with different pole pitches. The sizes of the test pieces were 32 mm x 32 mm (A), the test 16 mm x 16 mm (B), and the pole pitches of the pole stripes were 2, 3, 4, 5, 6, 7, or − 8 mm. Based on the knowledge described above, a striped pole wider than 2 mm was filled with lines with a 1-mm interval.

We prepared a holding-force measurement instrument (Figure 7) and test pieces A and B for each pole pitch and measured the holding force generated between striped pieces with the same pitch.

Test piece A was fixed vertically on the instrument, and test piece B was attracted to A. We attached a plastic bag to test piece B and injected water into it drop by drop until the test piece B detached and fell. The weight can be seen in the digital scale under the instrument (minimum unit = 0.1 g). We recorded the weight when test piece B detached and calculated the weight as holding force. The measurement was repeated five times for each pitch. The results are shown in Figure 8.

According to the results, the holding forces increase with the narrower pole pitches. The maximum value of the averaged holding force was 16.09 g/cm^2, obtained for the magnetic sheets with 2-mm pole pitch. This is considered to be due to the concentration of the magnetic flux.

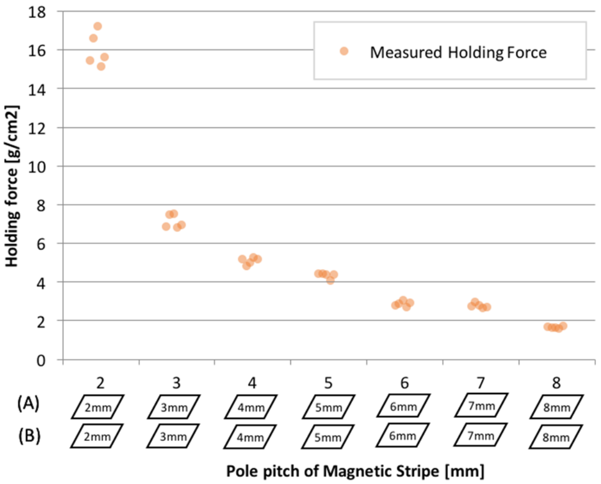


Figure 8. Holding force generated between a pair of striped pieces of magnetic sheet with the same pitch.

Intensity Design

Next, we tried to control the intensity of the texture without changing the spatial frequency of the haptic texture.

The intensity of the haptic stimuli depends on the holding force between the magnetic sheets. For the control of the magnetic force, we focused on the area ratio of the two magnetic sheets which is generating attractive and repulsive force. Using the area ratio, the total magnetic force between the two magnetic sheets can be estimated two dimensionally.

For example, when the two stripe-patterned magnetic sheets with 2-mm pole pitch stick to each other, the area ratio of the area of attractive force to the whole sheet is 100%. Then, when one sheet moves 1 mm perpendicularly to the stripe, the attractive force and the repulsive force is balanced, and The attractive force area ratio is 50%. Similarly, when the sheet moves another 1 mm, the whole area of the sheets generates strong repulsive force, and the attractive force area ratio is 0%. Thus, a firm macrotexture is displayed (Figure 10, top).

On the other hand, when two stripe-patterned magnet sheets, one with 2-mm pole pitch and another with 6-mm pole pitch are rubbed together, the attractive force area ratio of the two sheets is 33.33~66.67% (Figure 10, middle). As the area ratio of attractive force area approaches 50%, the magnetic attractive/repulsive force balances. Thus, the two magnetic sheets can display a weakened macrotexture without changing the spatial frequency of the haptic texture.

Besides, the attractive force area ratio between the 2-mm-pitch magnetic sheet and the test sheets with 4-mm-pitch sheet were always 50% (Figure 10, bottom). The attractive force generated between the S-pole and N-pole and the repulsive force generated between S-pole and S-pole and N-pole and N-pole will be constantly balanced.

These examples show that, by preparing the different pole-pitched magnetic sheets, the different intensities of the macrotexture can be displayed without changing the spatial frequency. Thus, we examined the holding force between two sheets with different pole pitches, ranging from 2 to 8 mm.

The measurement procedure was the same. The measured holding force and the calculated maximum attractive force area ratio are shown in the graph (Figure 9). As estimated from the attractive force area ratio, the result shows that the two magnetic sheets with 2-mm-pole-pitch generated a strong holding force, and the holding force between the 2-mm-pole-pitch magnetic sheet and the 6-mm-pole-pitch sheet was the second best.

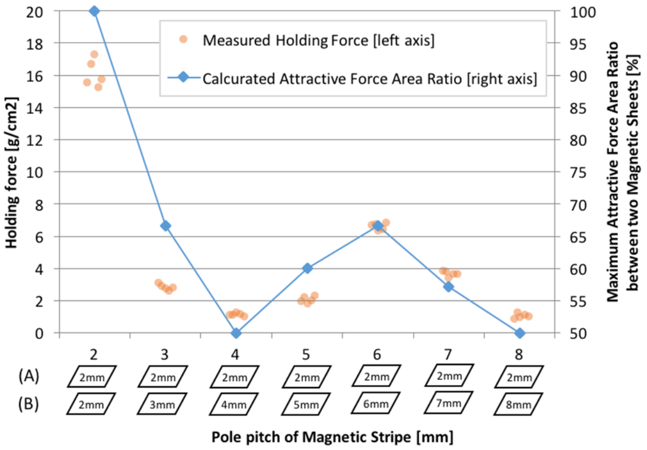


Figure 9. Holding force between the two pole-pitched sheets of different size and the maximum value of calculated attractive force area ratio.

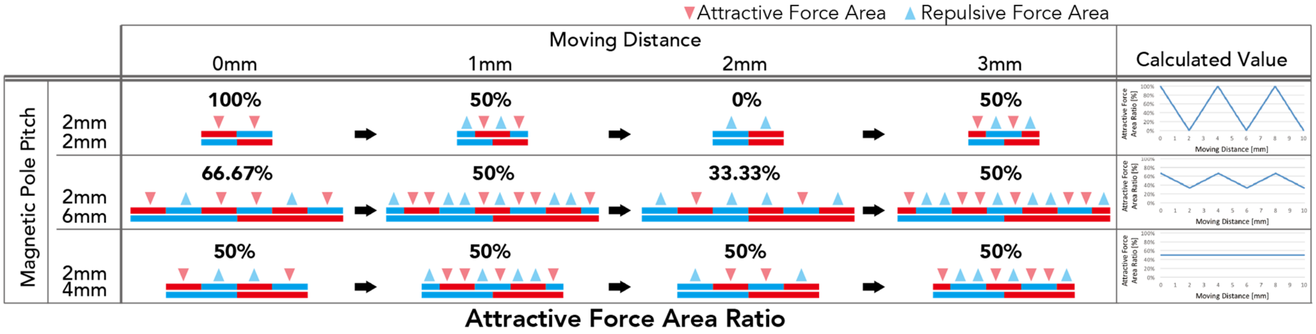


Figure 10. Estimation of the intensity of the magnetic force between the two different magnetic patterned sheets.

The spatial frequency of the macrotexture generated by the two magnetic sheets with different pole pitches is determined by the smaller pitch of the two magnetic sheets. When the 2-mm-pitch sheet was rubbed against the test piece with different pole pitches, the spatial frequency of the macrotexture was always the same (4-mm wavelength), which can be explained by the attractive force area ratio.

One-to-One Correspondent Macrotexture Design

On the basis of the above results, we also established a design approach for a one-to-one correspondent macrotexture. With this approach, for example, magnetic sheet (a) displays strong haptic stimuli on (a') but does not on (b') or (c').

Based on the magnetic force estimation using the attractive force area ratio, we changed the magnetic patterns from a striped pattern to a checkered one for the selective haptic design. In the conditions for the stripe-patterned magnetization, even if the magnetized pitches of the two magnetic sheets were different, some pairs of magnetic sheets (like a pair with the 2- and 6-mm pitch) generated haptic stimuli. On the other hand, the 2-mm-pitch checker-patterned sheet generated haptic stimuli only to another sheet with the same pitch and pattern.

Estimation

For example, with a 2-mm-pitch striped magnetic sheet and a 6-mm-pitch striped magnetic sheet, the maximum attractive force area ratio will be 66.67%. However, when the sheet is magnetized with a 2-mm-pitch checker pattern and a 6-mm-pitch checker pattern, the maximum attractive force area ratio will decrease to 55.56% (Figure 11). When the attractive force area ratio is between 40 and 60%, the magnetic force is almost canceled. Therefore, when the holding force is less than 2 g/cm^2, it will be hard to feel the macrotexture through magnetic sheets with the size of 16 mm x 16 mm. When a 2-mm-pitch checker-patterned magnetic sheet is rubbed on a 6-mm-pitch checker-patterned one, no haptic stimuli can be felt through the sheets.

Figure 12 shows the calculated maximum attractive force area ratios between two magnetic sheets magnetized with the stripe patterns and checker patterns with 2- to 8-mm pitches.

By changing the pattern from striped to checkered, the number of conditions where the attractive force area is over 60% is reduced from 14 to 6 (except same pitch) in the total of 21 conditions of different pitches. For example, with the 2-mm-pitch checker-patterned magnetic sheet, the maximum attractive force area ratio will be less than 60% in all conditions except the 2-mm-pitch one.

Measurement

Based on the estimation, we examined the holding force between two sheets with stripe and checker pattern, ranging from 2 to 8 mm (Figure 13). The measurement procedure was the same as before, and the value is the averaged value.

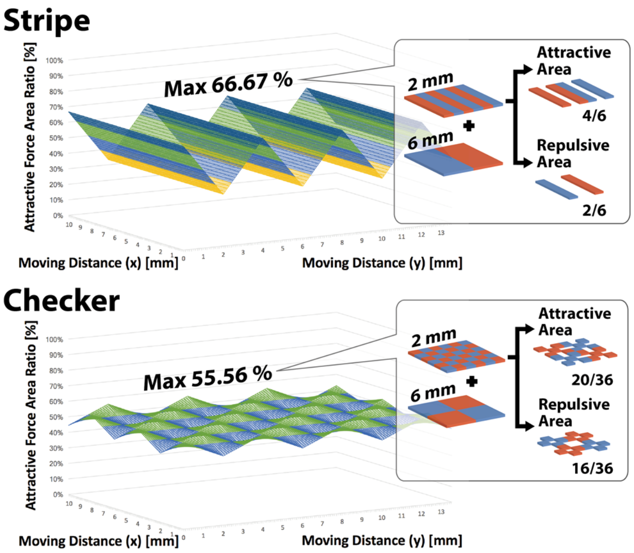
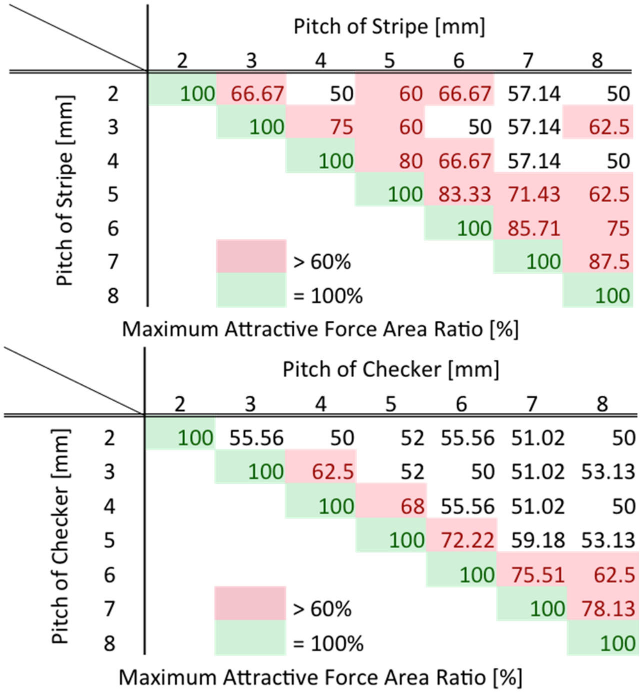


Figure 11. The attractive force area ratio of the magnetic sheets with two different pitches (2 mm and 6 mm) approaches 50% when it is plotted with checkered pattern, indicating that the haptic stimuli are weakened.



		Pitch of Stripe [mm]						
		2	3	4	5	6	7	8
Pitch of Stripe [mm]	2	100	66.67	50	60	66.67	57.14	50
	3		100	75	60	50	57.14	62.5
	4			100	80	66.67	57.14	50
	5				100	83.33	71.43	62.5
	6					100	85.71	75
	7		🟥	> 60%			100	87.5
	8		🟩	= 100%				100

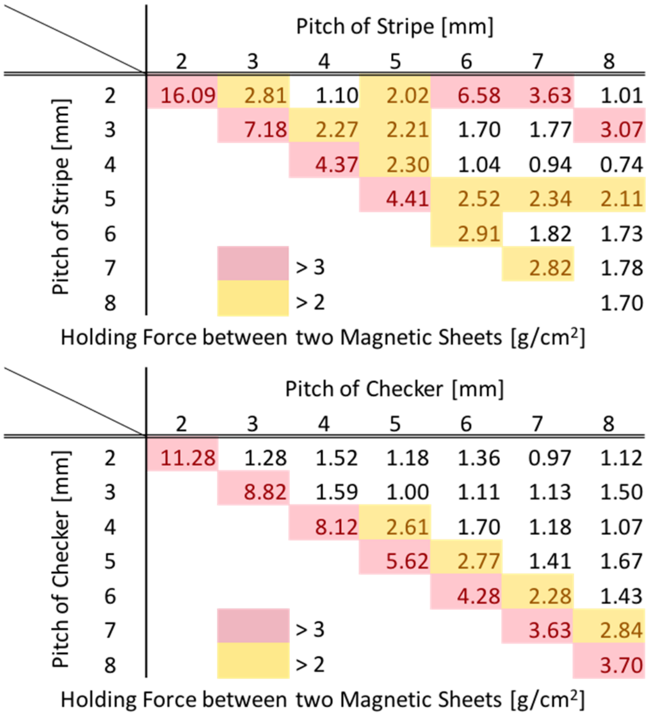
Maximum Attractive Force Area Ratio [%]

		Pitch of Checker [mm]						
		2	3	4	5	6	7	8
Pitch of Checker [mm]	2	100	55.56	50	52	55.56	51.02	50
	3		100	62.5	52	50	51.02	53.13
	4			100	68	55.56	51.02	50
	5				100	72.22	59.18	53.13
	6					100	75.51	62.5
	7		🟥	> 60%			100	78.13
	8		🟩	= 100%				100

Maximum Attractive Force Area Ratio [%]

Figure 12. The difference in maximum attractive force area ratio between stripe (up) and checker (down) patterns.

As a result, the checker pattern with the pitch of 2, 3, 4, 6, and 8 mm can display a macrotexture with different frequencies independently of each other. With the checker pattern, we achieved the design of a one-to-one correspondent haptic surface on the magnetic sheet. Moreover, the checker-patterned magnetic sheets generate haptic stimuli with horizontal motion and with vertical motion as well.



		Pitch of Stripe [mm]						
		2	3	4	5	6	7	8
Pitch of Stripe [mm]	2	16.09	2.81	1.10	2.02	6.58	3.63	1.01
	3		7.18	2.27	2.21	1.70	1.77	3.07
	4			4.37	2.30	1.04	0.94	0.74
	5				4.41	2.52	2.34	2.11
	6					2.91	1.82	1.73
	7		🟥	> 3			2.82	1.78
	8		🟨	> 2				1.70

Holding Force between two Magnetic Sheets [g/cm^2]

		Pitch of Checker [mm]						
		2	3	4	5	6	7	8
Pitch of Checker [mm]	2	11.28	1.28	1.52	1.18	1.36	0.97	1.12
	3		8.82	1.59	1.00	1.11	1.13	1.50
	4			8.12	2.61	1.70	1.18	1.07
	5				5.62	2.77	1.41	1.67
	6					4.28	2.28	1.43
	7		🟥	> 3			3.63	2.84
	8		🟨	> 2				3.70

Holding Force between two Magnetic Sheets [g/cm^2]

Figure 13. Averaged holding force of stripe (up) and checker (down) patterns.

APPLICATIONS

Using the design method, we created several examples of Magnetic Plotter applications.

Magnetic Stamp

This example shows that the magnetic fields can be designed freely by using common drawing software. The shape of the magnetic fields can be displayed on a child's magnetic drawing board [Figure 14 (a)].

When two polarities are plotted in narrow areas, the magnetic flux will be concentrated. Therefore, the striped magnetic sheet can attract more iron sand in the toy board to change the color to black. In contrast, when a broad pole (> 10 mm x 10 mm) is plotted, no magnetic force will be detected in the middle of the magnetic pole. The surface magnetic flux density is less than about 5 mT. By combining these two patterns, we can create original magnetic stamps.

Texture Book: Haptic Picture Book

This is an example of designing multiple haptic stimuli without an energy source [Figure 14 (b)]. By combining the magnetic patterns and printed pictures, a normal picture book becomes a fun touch picture book, or "texture book". It is possible to present different stimuli at different spots. And if the magnetic pattern of the "cars" (magnetic sheet to place) are different, it is possible to present a different touch even if the design of the "road" (magnetic sheet to underlay) is the same. Moreover, since the book does not require a battery, it is easy to carry, just like a normal picture book.

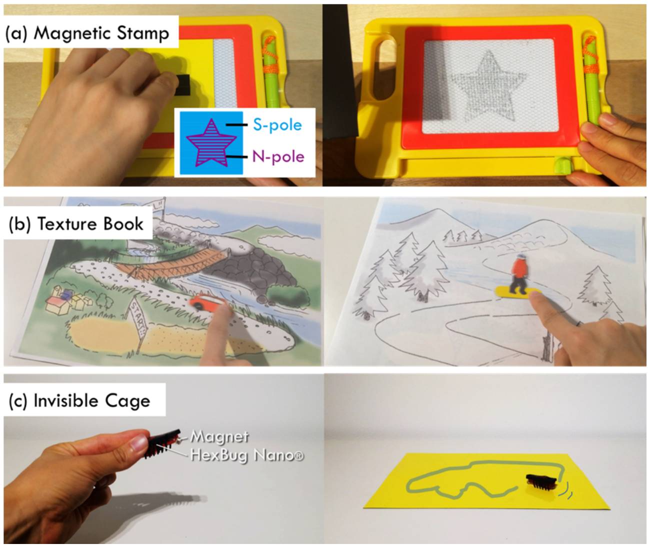


Figure 14. Application examples. (a) Magnetic Stamp. (b) Texture Book. (c) Invisible Cage.

Invisible Cage

This is an example of a force field presentation to a physical object. The physical forces of the magnetic sheets affect tangible objects as well [Figure 14 (c)].

HEXBUG Nano [34] is a small robotic toy. A vibration motor and batteries are embedded in the small body, and a brush forms the legs and feet. When the power is turned on, the robot moves like an insect.

When a tiny magnet is put on the bottom of the robot and the robot is placed on a magnetically plotted sheet, it can run only in the area determined by the sheet. The path and field can be designed by the magnetic pattern. The effect is like an invisible cage. This method of making an enclosure without a physical barrier can be applied to other physical things easily, such as a safety stopper or a passage for blind people.

DISCUSSION

We introduced Magnetic Plotter as a digital tool for DIY magnetic functions and described a method for designing magnetic fields with inexpensive materials and equipment. Our contributions lie in the engineering domain. We did not present a user study of the plotter because the usability of the plotter and the drawing software are the same as the original products.

Neither did we perform user tests to assess the haptic sensations produced by the system. This is because this has already been done for a variety of shear force displays and addressed in the tactile research literature [29,30,32].

Instead, we devoted most of the descriptions to our novel sheet-shaped device that can generate finely designed magnetic fields, covering the selection of the medium, how to plot, the design method of the haptic stimuli, and the estimation of the magnetic force. Therefore, here we describe the limitations and possibilities of Magnetic Plotter.

Limitations

As limitations, we describe mainly the resolution and the strength of the magnetic field.

In this study, for handiness of the system, we used an ordinary magnetic rubber sheet. Stronger magnetic fields can be presented by using a neodymium magnetic rubber sheet: the surface magnetic flux density exceeds 100 mT in 1-mm thickness with the same softness and lightness as a ferrite magnetic sheet. However, since a neodymium magnetic sheet requires more concentrated magnetic flux density (i.e., a laboratory-level magnetizer) to rewrite the polarities and is a kind of high-end product (60 US$ in A4 size), it might not be suitable for home fabrication.

Similarly, we selected the 2-mm-diameter neodymium magnet as a plotting head. Therefore, the smallest writable size is a circle of 2-mm diameter. However, like the magnetizer in FluxPaper [24], it is possible to make the magnetic resolution finer by using a cone-shaped piece of magnetic yoke to concentrate the magnetic flux of the neodymium magnet. If the resolution become finer, this approach can be applied to generate a micro-texture or nano-texture.

Next, we discuss the protective film of the magnetic sheet. In this study, we used a magnetic sheet coated with a protective film on one side. We plotted magnetic polarities on a surface without a protective film in consideration of the decrease in magnetic flux density. The magnetic flux density of the neodymium magnet used in this study will become less than 300 mT when the distance from the neodymium magnet is 0.2 mm or more. Therefore, the magnetic sheet should not be covered with a piece of paper or a film before magnetic patterns have been plotted.

For the same reason, when there is 1 mm or more gap between the two magnet sheets, the fingers cannot feel a haptic sensation because the magnetic fields are weakened considerably. For the proper haptic presentation, the high limit on the distance between the two magnetic sheets is about 0.5 mm (3 to 5 sheets of stacked ordinary paper).

Design Possibilities

On the other hand, the design of the magnetization pattern still has room for expansion. Different textures could be generated by plotting curving lines, dot patterns, lattice patterns, and asymmetry patterns using Magnetic Plotter. Moreover, there is also a possibility of interaction by changing the shape of the magnetic field by rotating, cutting, stacking, or folding the magnetic sheet.

Additionally, if magnetic field editing software or a plug-in, and a dedicated machine for magnetic plotting become available, our method is likely to become more useful and widespread. This remains as future work.

As a Home-use Magnetic Editing Tool

The magnetic sheet is a mass-produced material, but it is not disposable because the plotter can overwrite the magnetic fields repeatedly many times and the sheet can be washed with water. Further, even if there is no digital plotter at home, the magnetic field can be written manually. In addition, as it is easy to paste the sheet onto devices or objects, the sheets provide haptic textures to things in our daily life. This method is useful for rapid prototyping of haptic applications or for haptic workshops.

CONCLUSION

In this paper, we presented a method for creating magnetic fields in the home with inexpensive materials and home-use equipment: a magnetic rubber sheet, a neodymium magnet, and a desktop digital plotting machine. We named the system Magnetic Plotter and developed a prototype. Through the investigation of the system, we established a design method for non-electric macrotexture display. By controlling the spatial resolution and the shape of the magnetic fields, the macrotexture generated between two magnetic rubber sheets can be designed.

Moreover, we implemented an one-to-one correspondent macrotexture on the magnet sheet. A piece of magnetic rubber sheet plotting a checker pattern of polarity generates a macrotexture only where the checker pattern with the same pitch is plotted.

Based on the design method, we demonstrated several applications with the prototype and discussed the possibilities and limitations.

Additionally, a notable feature is that the fabrication process can be completed by using a desktop digital plotter and commercially available materials. The in-expensive magnetic sheet is flexible and waterproof, and the polarity pattern is re-writable. This method is very well suited for rapid prototyping, home fabrications, and workshops.

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