FluxPaper: Reinventing Paper with Dynamic Actuation Powered by Magnetic Flux

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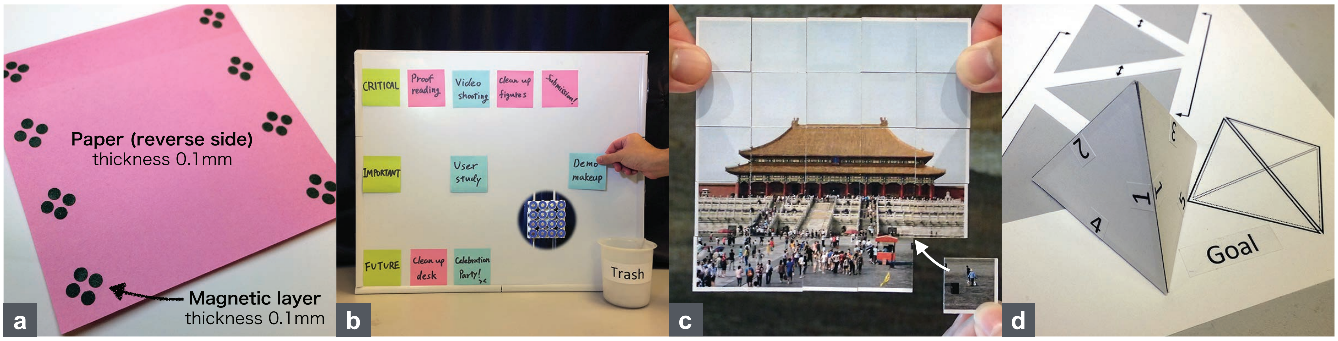

Figure 1. FluxPaper and its applications: (a) Basic structure of FluxPaper, (b) Automated To-do list by whiteboard and electromagnet header behind the board, (c) Creating picture puzzle using 25 pieces of self-aligned paper, (d) Tetrahedron model using self-aligned paper.

ABSTRACT
FluxPaper is a new paper-based medium that enables physical movement and dynamic interaction between a high-power magnetized paper and a programmable magnetic field. FluxPaper has a very thin patterned magnetic layer (0.1 mm) pasted behind the paper. A thin but strong neodymium-based magnet realizes fast, powerful, and precise physical actions while retaining the original characteristics of the paper that is widely used in our daily lives. Owing to an effective magnetic pattern and a computer-controlled magnetic field, FluxPaper can add new interaction modality to ordinary paper. We describe the functions of magnetized paper; challenges through realization; and the interaction scenarios in several applications, such as self-alignment, self-construction, floating on the board, and quickly picking out a target card from a stack.

Author Keywords
Active paper; paper interaction; magnetic flux; shape-changing;

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

INTRODUCTION
Paper is a common material used for several functions such as printed media for knowledge productive work, material for packaging, and folding into aesthetic designs (i.e. origami). In HCI research, as paper has become a common and affordable medium of user interaction and design, paper can be applied to computer manipulation. There are some existing concepts of enhancing regular paper such as moving or shape-changing functions [3]. In many cases, shape memory alloy (SMA) or other kinds of temperature-controlled materials are attached on the paper for deformation [12, 18, 19]. The system can control and change paper shape by adding heat with electricity or laser to the material. External energy is required for actuation, and complex wiring is often needed on the paper for controlling individual moving joints.

In this work, we reinvent paper with dynamic actuation powdered by magnetic flux. We create a magnetically controllable paper named FluxPaper and establish the technology to manipulate the paper's physical actuation by both of self-actuation (actuation without applying external energy), and computerized electromagnetic control. Our approach provides self-actuation capability to ordinary paper without applying external energy and removes complex wirings on the paper for controlling actuation.

In this paper, we will describe:

- Envisioning the future of paper interaction with magnetic manipulation by showing several possible applications
- Providing methods and techniques for producing thin and powerful magnetized paper
- Describing effective design for both pasting and magnetizing patterns and control systems, to build the application of magnetically actuated paper.

FLUXPAPER

FluxPaper is a magnetically controllable paper, and has a very thin patterned magnetic layer pasted or printed behind the paper (Figure 1 (a)). Although the magnetic layer is very thin (0.1 mm), a neodymium-based powerful magnet provides enough attractive or repulsive force for physically moving the pasted paper material. The cost of the magnetic layer actually used for proposed application is about U.S. $0.15 per a sheet of sticky note size.

FluxPaper can be handled in the same way as ordinary paper. According to the thickness of general paper, such as Post-it® sticky notes (0.1mm thickness) and general printer paper (72 g/m^2, 0.092mm thickness), we targeted to make the magnetic layer as thin as a paper substrate, thus current FluxPaper consists of 0.1 mm paper and 0.1 mm magnetic layer. Magnetic layer is usually placed on the bottom side of FluxPaper, so the face side can be used for printing. To make 0.1mm thickness of magnetic layer, we molded magnet powder made of very small magnet particles with epoxy resin. By using neodymium-based magnet powder, we succeed in generating a flexible but powerful magnetic paper.

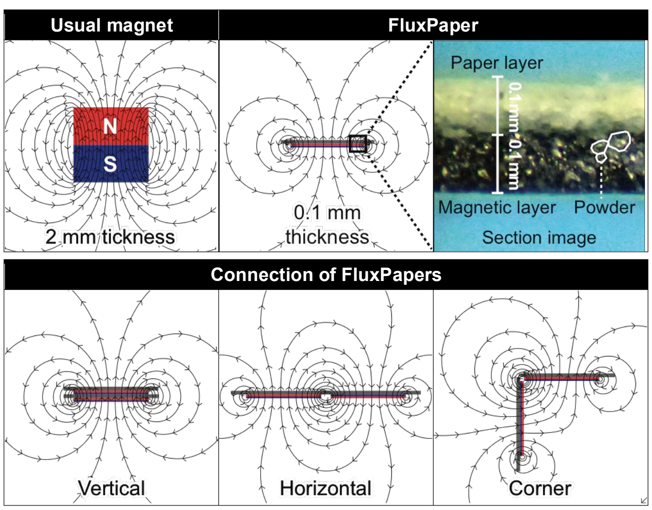

Figure 2. Illustration of FluxPaper and magnetic pole.

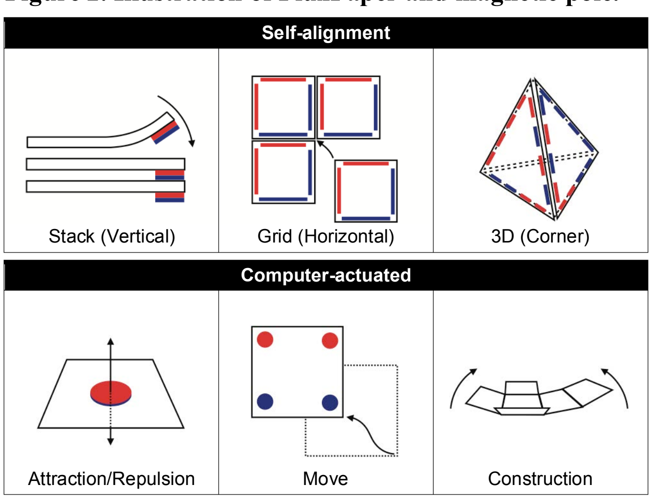

Figure 3. Possible design with FluxPaper.

Figure 2 shows the composite details of FluxPaper and compares these with an ordinary magnet, where lines of magnetic flux are simulated in a condition that relative permeability of the paper is the same as free space. According to the magnetizing direction, magnetic flux penetrates the paper surface (= surface normal direction), thus they can be used for stacking FluxPapers vertically. The magnetic flux around edge can be used for connecting FluxPapers horizontally and also making three-dimensional (3D) structure.

FluxPaper can add two kinds of actions to ordinary paper; self-alignment: the paper can attract other pieces of paper without external force; and computer-actuated: the paper is actuated by an external magnetic field. Figure 3 shows typical design and actuation patterns of FluxPaper. In self-alignment, it can be actuated without applying any external energy, and used for self-alignment functions for vertical stacking, horizontal connection with a grid, and making 3D shapes. In computer-autuated, an external electromagnetic field, such as computer-controlled electromagnets, can actuate FluxPaper, enabling many complex functions without attaching a bunch of wires on the paper material.

PAPER PRODUCTION

Figure 4 shows current "laboratory-level" production process of FluxPaper. It does not require huge plants and much electrical power. The process is as follows:

1. Mix the two mediums of epoxy in a bowl. Place the magnet powder in and mix again evenly.
2. Place the magnet paste on the paper and mold it by leveling off. Wait until it finishes hardening.
3. Cut and reshape the magnetic layer.
4. Magnetize it with a magnetizer by using two permanent magnets.

Magnetic Powder

The magnetic layer of the FluxPaper consists of bonded neodymium magnet powder and epoxy resin. We used the neodymium bond magnet powder (Molycorp Magnequench's MQFP 14-12-20000 [16]) that has a strong magnetic flux of 780–840 mT [mili Tesla] and is usually used for plastic magnets. The size of the particle is around 5 µm, which is small enough to make the composite thin magnetic layer pasted on the paper.

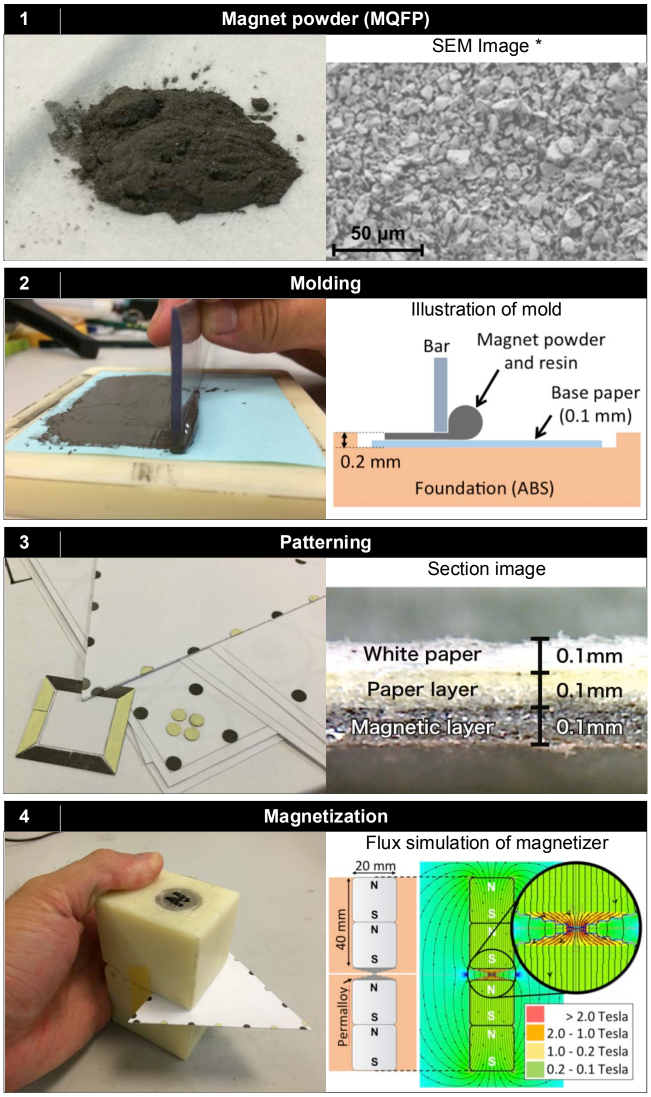

Figure 4. Laboratory-level production process. (*SEM image is cited from Magnequench's document [16].)

Solidification
Epoxy resin is one of the best solid preparations to make a strong conjugation between the paper and magnetic layers. We selected two-liquid epoxy adhesives (Loctite® E-20HP Hysol) for solidifying the magnet layer. Preliminary experiment reveals that the best mixing ratio of magnet powder to epoxy resin is around 5:1 in gram units. The density of the epoxy resin is 1.10 g/cm^3; the apparent density of magnet powder is 1.69 g/cm^3, with a theoretical density of 7.4 g/cm^3; and the actual volume ratio of magnet to epoxy resin is 3.25:1, thus the content of magnet powder in the composite is about 76.5% by volume.

Molding and Patterning
Shaping and molding the magnet layer is particularly challenging. Because of its thickness of 0.1 mm, we had to design a special apparatus for molding. Since there are no tools that can process a rolling mill in a normal laboratory, we leveled off the magnet epoxy paste on the paper before hardening the epoxy. We made an ABS plate with a level of 0.2 mm (= 0.1mm paper + 0.1mm magnetic layer) by a milling machine. For molding, we put the paper on the lower level and level it off by placing a straight stick on the upper level. After the leveling, the polypropylene sheet should be placed on the leveled magnetic layer to flatten the surface. After the magnetic layer hardens, the FluxPaper is cut and pasted on the other paper substrate (White paper in Figure 4 (3, right)). Therefore, current FluxPaper's thickness is not 0.2 mm but 0.3 mm, however, magnetic power is still enough for proposed applications.

Magnetization
Generally, magnetization of neodymium magnets requires a high magnetic flux density by emitting the pulse current about 10,000 A. However, it is difficult to use or build such a danger high-voltage apparatus in a normal laboratory. Our approach was to use a non-electronic device to generate a large magnetic field at the thin gap between two magnets. We placed two pieces of magnetic yoke made by PB permalloy between the two magnets. PB permalloy is a type of Ni-Fe alloy and has high permeability that allows magnetic flux to more easily pass through. Figure 4 (4, right) shows the design of the non-electronic handy magnetizer. In this apparatus, we use two cylinder shaped neodymium magnets (N35, 11900 gauss, 20 mm in diameter and 20 mm in height). The ABS container holds the magnets and permalloy. The surface flux density of the bare magnet is 500 mT. Permalloy-based yoke creates a high magnetic flux density of up to about 3.5 T at the narrow gap between two blocks. As the required magnetic flux density for magnetizing the neodymium magnetic powder is between 1.2 T and 2.0 T, the magnetic flux density of the magnetizer is strong enough for magnetizing the magnetic layer of FluxPaper.

Comparison with Existing Magnet Sheets
There are some magnet sheets for holding small items, and magnet papers for printing labels or pictures. These products are basically made from plastic or rubber sheet that contains the magnetic powder. However, these magnet sheets do not have enough magnetic power for targeted applications. They use low coercivity magnetic powder or density of magnetic powder is reduced for cost reduction. Magnetization patterns are also different. Ordinary magnet papers adopt periodic striped or checkered patterns for increasing the attractive force on the metal plate. On the other hand, by magnetizing with surface normal direction, FluxPaper has large magnetic flux leakage that is used not only for sticking on the metal plate, but also stacking vertically and connecting horizontally with other piece of FluxPaper. Therefore the suitable magnetization pattern may vary from each application. In addition, FluxPaper should be strong against the external magnetic field. For example, when a small neodymium magnet (5mm diameter, 10mm height) is placed on the sheet, FluxPaper can keep the same magnetic flux as when it is magnetized, but the

ordinary products lose their magnetic flux and re-magnetized.

Safety and Measures

Small particles of magnet powder (less than 100 μm) are dangerous and fatal to lung health, and its chemical composition contains heavy metal. A dust mask must be worn during treatment and hands should be washed to remove powder from the skin. However, after curing epoxy resin, the magnetic layer is durable, sealed, and as safe as usual magnet products and rubber magnets. Thus the structure of FluxPaper can bear in long-term use. Even if the magnetic layer is cracked, the broken piece is still covered with epoxy resin, which is a safe and popular material for printed circuit boards (PCB) and making waterproof paper.

CHARACTERISTIC ANALYSIS

We analyzed very thin magnetic layers with magnetic field simulation software (ViziMag 3.18) and conducted two types of experiments on the magnetic flux density to compare and verify with normal magnets. These experiments were in preparation to prove the effectiveness of FluxPaper applications. Experiment #1 measured the repulsion force of two types of samples against the magnetic field. And experiment #2 compared the repulsion force among different ratios of magnetic layer areas on the paper.

Magnetic Flux Distribution Analysis

We compared two types of magnetic layers, shown in Figure 5. Each layer has 0.1 mm thick and is magnetized. One has a magnetic layer space of 0.5 mm every 2 mm, the other one is a non-slit type. The total area of the magnetic layer is 1 cm^2 each, thus there is no difference of amounts of magnetic powder between two samples.

The results and analysis are shown in Figure 6, which indicates a section view of samples. The magnetic flux is illustrated as the lines that represent magnetic flux lines, and color is the density of the magnetic flux; red, yellow, and green colors represent strong densities. The paper with the slit has more surface flux density than the paper with no slit, which means that the slit design emits a leakage flux outside. We also check the results with a gauss meter to probe the surface of the samples.

Slit Design and Repulsion (Experiment #1)

We wanted to know whether the gross attraction and repulsion force is different between slit and non-slit designs. This is important for designing the pattern of magnetic layers on the paper to strengthen the attraction and repulsion force affected from the external electromagnetic field.

Figure 7 shows our design of an experimental apparatus and arrangement. For this experiment, we reused the same slit/non-slit samples (Figure 5). We were using electronic weighing instruments—with an accuracy of 0.1 g, up to 200 g—foundations for place, a transparent plastic plate, a

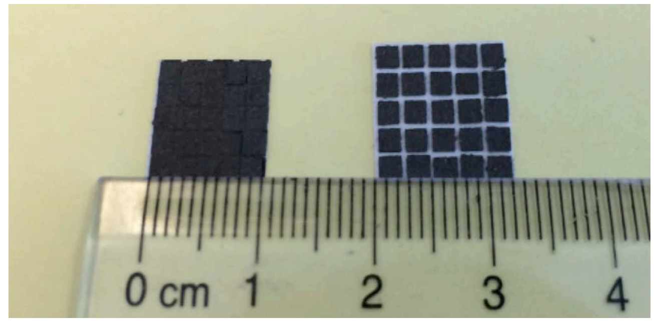

Figure 5. Samples of FluxPaper with non-slit and slit design.

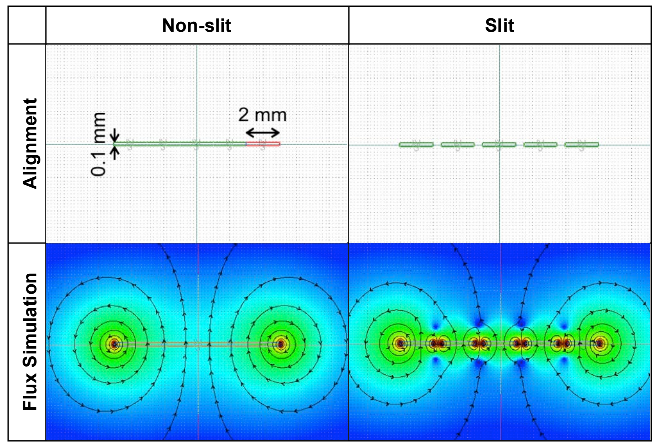

Figure 6. Analysis of magnetic flux for two designs of samples. Slit-designed FluxPaper (right) has a strong magnetic field between slits.

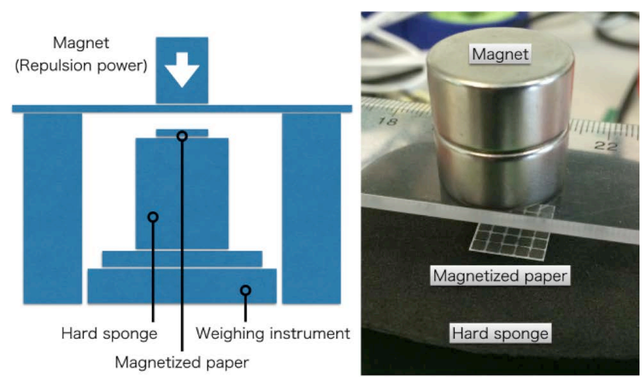

Figure 7. Measurement apparatus for repulsion and actual configuration with the magnet and the sample.

hard sponge, and a magnet—a 20 mm in diameter and 20 mm in height, N35 neodymium magnet. We placed the samples on the hard sponge to avoid the attraction force to the weighing instrument caused by a magnet. Using this apparatus, the distance between the sample and magnet was fixed at 11 mm, enabling the precise measurement of repulsion force. We placed the magnet just above the sample. With this method, we found no difference in repulsion force between the two samples. The average from ten operations was 6.7 g for slit designs, and also 6.7 g for

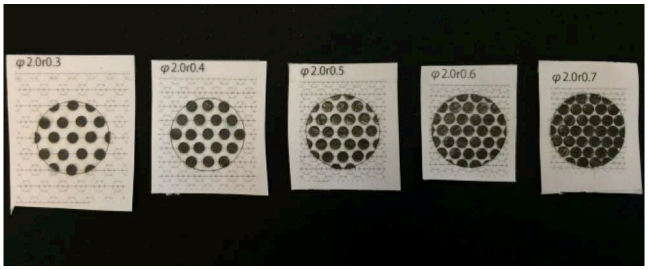

Figure 8. Different area ratio (30%, 40%, 50%, 60%, 70%) of magnetic layer on samples.

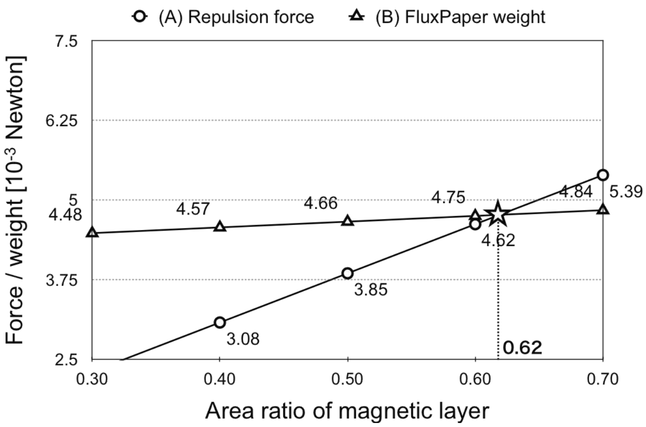

Figure 9. Results of repulsion force against the opposite magnetic field. An equilibrium point of efficient area ratio can be solved from the cross point.

non-slit designs, which means that the slits on the magnet layer do not affect the gross repulsion force of the magnetic layer against the external magnetic field.

Magnetic Area Ratio and Repulsion (Experiment #2)

We prepared five sheets for area ratios at 30%, 40%, 50%, 60%, and 70% of the magnetic layer, as Figure 8 shows. All sheets are magnetized in the same magnetic field (2 Tesla). The experiment was carried out with the same apparatus as shown in Figure 7. In this experiment, the distance between the sample and the magnet was 12 mm.

Figure 9 is a plot of (A) the relationship between gross repulsion force and the area ratio of the magnetic layer and (B) paper weight calculated from the weights of paper (76 mm square Post-it®), magnetic layer (4 points of 13.65 mm diameter, the same as samples). This result described the whole amount of the magnetic layer contributed to the gross attraction (and the repulsion) force to the external magnetic field. In the magnetic field density of 1/20 from experiment #2, the cross point showed that 0.62 was balanced.

These experiments indicated that total repulsion force is just affected by the total amount of magnetic powder and not by the slit design. However, the simulation also indicated that properly designed slit could generate high magnetic field between slits. It can be effectively used for vertically stacking applications.

FLUXPAPER WITH SELF-ALIGNMENT

In this section, we describe three approaches to utilize FluxPaper's magnetic flux attraction force without applying external energy; vertical stacking, horizontal draw-up along the grid, and making a complex structure in three dimensions (Figure 10). Since FluxPaper retains the attraction force between papers loosely, , we can design several re-coupling and movable joint functions. In addition, because of the high flux density on FluxPaper, the magnetic layer can be inserted between the two papers and both surfaces could be used for printing.

Self-stacking, easy to arrange (Figure 10 (a))

The two surfaces of FluxPaper that are magnetized as S and N poles attract each other, which means FluxPapers which have the same magnet layer pattern and the magnetized pole can be stacked in the same row. Even if the paper is thrown and roughly placed on the other paper, the paper moves and stacks automatically. This feature realizes neat desktop even when bunch of documents are piled up.

Horizontal connection with grid (Figure 10 (b))

FluxPaper provides the self-connection function by using leakage magnetic flux on the side of the piece. Pieces of FluxPaper can be connected to the edge of next piece when one piece is coming close to the next piece. In Figure 1 (c), using 25 separated pieces of the square FluxPaper, we built up one photograph. Finally, we could lift a complete puzzle by two hands with one metal bar behind the upper side.

Complex 3D structure (Figure 10 (c, d))

Because of the magnetic flux emitted from the magnetic layer, each FluxPaper has a magnetic flux around the surface or edge. These flux leakages can attract or repel each other, also in the 3D structure. We show an example of using FluxPaper to build a rectangular tetrahedron. In

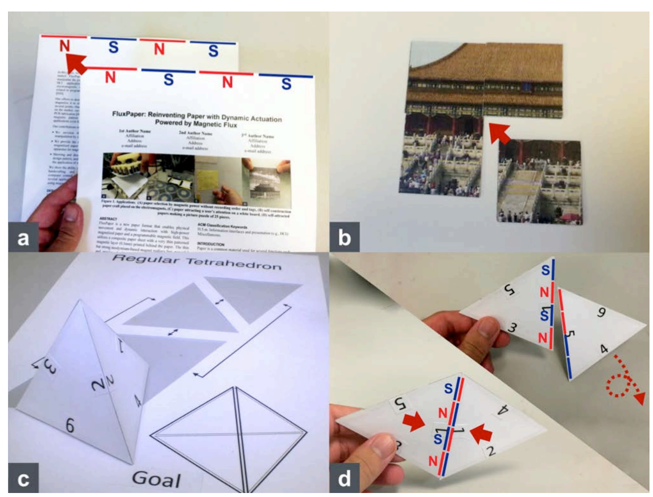

Figure 10. Examples of Self-alignment: (a) Vertical stacking, (b) horizontal connection with grid, (c) Self-connected tetrahedron model, (d) Only a correct combination with the same number of edges, can be connected. S and N indicate internal magnetic pattern.

this example, four pieces were connected to each side of the pieces, and each side had a number that represented the right connection to the other side. Because the magnetic flux has two poles, the paper can attract and repel according to the combination of magnetization patterns. When the combination or direction is wrong, FluxPaper will not be connected and the two sides will repel each other as shown in Figure 10 (d). Users can understand the correct combination or direction from the magnetic repulsion feedback of the FluxPaper.

AUTOMATED WHITEBOARD

A whiteboard is one of good candidate for utilizing FluxPaper's ability. We created an automated whiteboard that has movable electromagnet header with a special XY table behind the board (Figure 11). We also designed the FluxPaper-based sticky memo pad that has specially designed magnetic and adhesive areas.

Hardware Structure

A whiteboard consists of aluminum frames, two motors and belts, one electromagnet header, and one Arduino-based micro controller with a stepping motor and DC motor controllers. The board size was 600 mm x 500 mm (W x H), the XY table moved 400 mm x 320 mm, and the electromagnet header size was 80 mm x 80 mm. The electromagnet header was moved by the XY table with two motors. The header contained 4x4 (total 16) electromagnets. The electromagnet was 20 mm in diameter and had an 8 mm center area of iron core surrounded by a coil. The microcontroller and motor driver IC controlled 16 electromagnets. Each electromagnet consumed 0.25 A when 12 V was applied, then 4 A for all. The average surface flux density was 50 mT when 12.0 V was applied to the coil of the electromagnet. Because of the thickness of the whiteboard (3mm), actual flux density effects to the FluxPaper were about 20 mT.

Tracking, Pointing, and Moving

A whiteboard can detect the paper position as well as the color and text written on the paper by capturing the image of the board on camera. Camera tracking can determine the position of each paper. Through processing with OpenCV, the fluorescent color was extracted and the paper shape was detected. Each paper attached to the board had adhesive area pasted on the backside. By using the electromagnet header, it could be moved to other positions or trashed into the box beside the board. Because the minimum step of the stepping motor was 0.01 mm on the XY table, the XY table could manipulate the head and paper precisely.

Paper Design with Adhesive

Figure 12 shows the magnetic layer behind the paper. There are two kinds of areas, one is the combination area of magnetic layer and adhesive, and the other is the simple magnetic layer. When moving on the whiteboard, non-adhesive magnetic areas are attracted and the adhesive area is repelled by the electromagnet header. When the paper is moved to the destination, adhesive areas are attracted and keep sticking after magnetic power is dissolved. Moreover, when all magnetic areas are repelled, the paper will fall down.

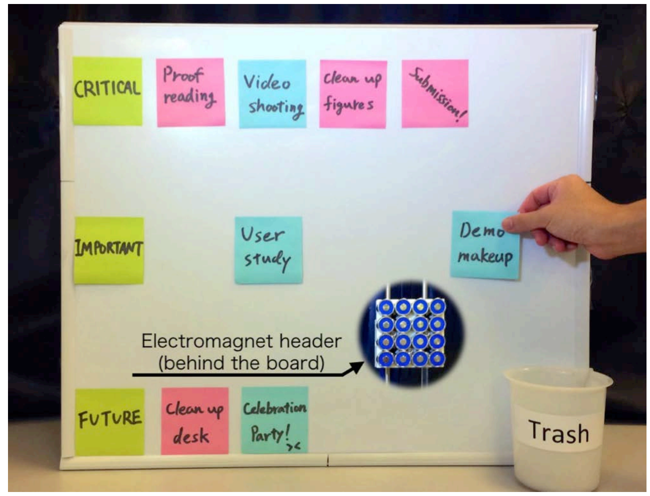

Figure 11. Automated and magnetic white board: Movable electromagnet header behind the board.

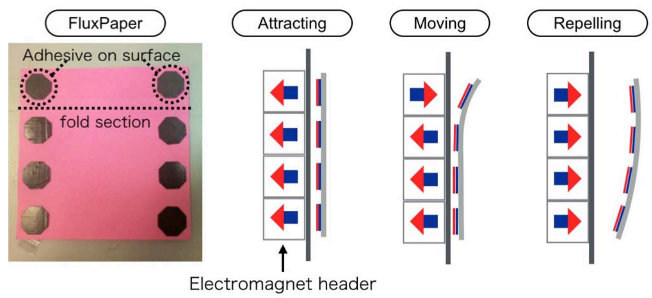

Figure 12. FluxPaper design and actuation patterns. When repelling the top section of the paper, the paper attached on the board with adhesive is taken off.

Paper Expressions

On the whiteboard, designing paper expression realizes a new modality of interaction via magnetically actuated paper media by attracting and repelling with the magnetic field. We designed four patterns of paper expression shown in Figure 13. For example, to provide notification and user attention, changing the magnetic field notifies the users. In addition, by waving or curl-up expression, the system can obtain the user's attention, and by vibration, the system can react to a user's behavior when the user is going to touch or remove the paper. When the user is going to obtain the wrong piece of paper from the whiteboard, the whiteboard attracts the paper so that it cannot be removed from the board.

Practical Tasks

An automated whiteboard and FluxPaper provide many opportunities to design real-world interactions via paper. We show two particularly practical applications.

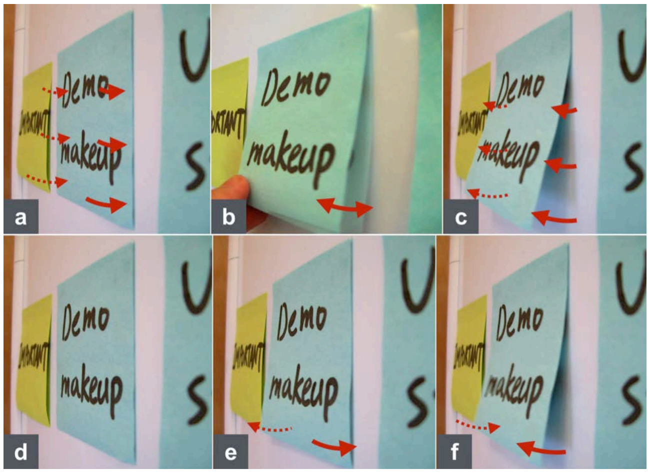

Figure 13. Paper Expressions: (a) attraction to avoid user to remove the paper, (b) vibration to notify the task is not finished or failure, (c) curl-up to get user's attention, (d, e, f) waving makes noise to notify.

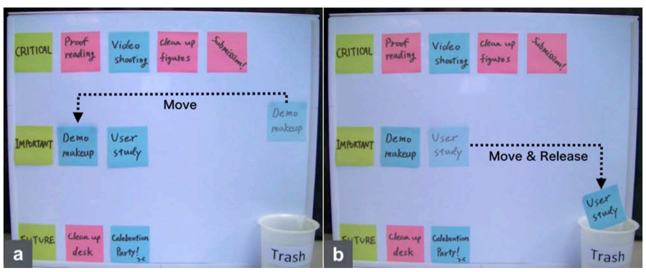

Figure 14. (a) Re-arrangement of paper, and (b) wasting cards.

To-do management (Figure 14)

To-do management is one of the important tasks that a user would require to be managed by computers. FluxPaper and the whiteboard realize the collaboration between human and computer via a medium of paper. When users write something on the whiteboard, they must check and remove it on their own. In FluxPaper application, the system detects and recognizes the text on the paper. For example, the system can be implemented to judge the to-do task with the schedule attribute. Therefore, when the scheduled task reaches its time, the whiteboard starts to notify the paper to the user with several interactive expressions.

Re-arranging and wasting

As people use a piece of paper for brainstorming and collaboration, FluxPaper also can help group interaction with paper items. According to image recognition, FluxPaper pasted on the whiteboard can be arranged by color, order, content, and other attributes related to the items. The system schedules and calculates the trajectory to move the papers to an ideal position while avoiding collision with other papers. When the item is finished or the system judged to trash, the item can be moved to trash automatically.

ONE-TOUCH PICKUP FROM STACKED CARDS

Usually, the card cannot be selected without any preparation, just by scanning the tag information one by one, such as with barcodes or magnetic tape, and it is impossible to select and pick up if it is stacked. FluxPaper enables the direct selection of certain cards from the stack without scanning of each cards.

Hardware and Control

Figure 15 shows a sample configuration of two electromagnet headers designed for selecting 8 FluxPaper-based cards. Top and bottom headers that have 16 electromagnets control magnetic flux to select the paper to be lifted up or allowed to fall down. Electromagnets control the output that matches the paper's magnetic layer that users want to obtain and they are connected to the microcontroller that enables control of the magnetic pole of 32 electromagnets placed on header equipment. There is a handle to grab the header and cables shown in Figure 16 (c). The system must know the pattern of the magnetic layer before operation; however, there is no need to know about the order of papers.

Paper Design

There are eight designs of magnetic layers for 16 points of magnet operation, with 2 points selected for each paper. (Figure 17) The magnet layer of each paper does not overlap the others. Testing with eight pieces of paper, each paper has enough power to lift the other paper up between the attracting header and attracted paper when the electromagnet is operated. Due to the limited number of electromagnet actuators, current patterning design is not rotational invariance, then the orientation of the cards must be aligned before stacking.

SELF-CONSTRUCTION

FluxPaper can be constructed in a magnetic field environment. The magnetic layer repels or attracts the magnetic flux emitted from the electromagnet, and a computer can fold or hold the paper. We are showing one

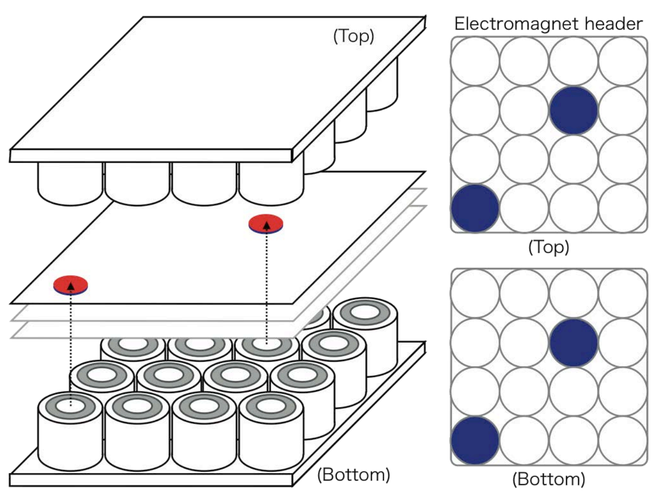

Figure 15. Image of one-touch card pickup system.

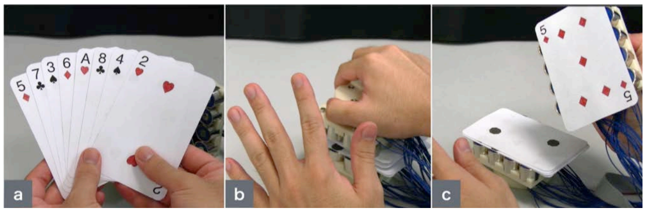

Figure 16. One-touch pickup application: (a) 8 magnetized cards, (b) Stacking cards and electromagnet operated to select 'the five' card, (c) Selecting 'the five of diamonds' from the stack.

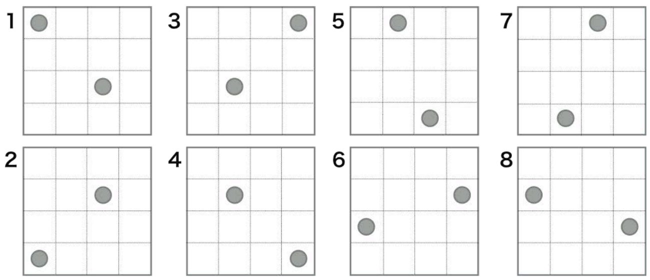

Figure 17. Sample card design of magnetized patterns.

example of a folding design for FluxPaper. Figure 18 shows the folding process to make a regular hexahedron from beginning to end. The paper placed on the electromagnet header has designed pattern on the surface that has two types of magnetic layer shape. The circle-shaped magnetic layer receives attraction force from the electromagnet and a line-shaped layer keeps the connection between sides after movement. Two of the sides support the building of the cube structure.

DISCUSSION AND FUTURE WORKS

Through three entire computer-actuated applications that handle FluxPaper, a magnetic field and its two directional powers actuate and make papers active, organic, and interactive. The shape and size of the electromagnets for generating the magnetic field limit flux density and fineness. The paper should match the apparatus used in this study. However, the functional design and magnetic flux density printed on the FluxPaper was precise and strong enough to realize the activity, shape-changing, and self-constructible paper with magnetic power.

Our future goal is to realize the automated printing system to print both the color ink and the magnetic material on paper to generate FluxPaper (Figure 19). The printer would include the usual inkjet header, special header of magnetic ink or thermoplastic magnetic filament, and computer-controlled magnetizer to magnetize the magnetic layer with a specific pattern. Moreover, by combining Ag ink-based circuit printing [9] and 3D printing technology, we will create many complex objects that include magnetic and electric components. With the help of computational design, users can automatically generate the paper format for building and constructing with a magnetic guide. We

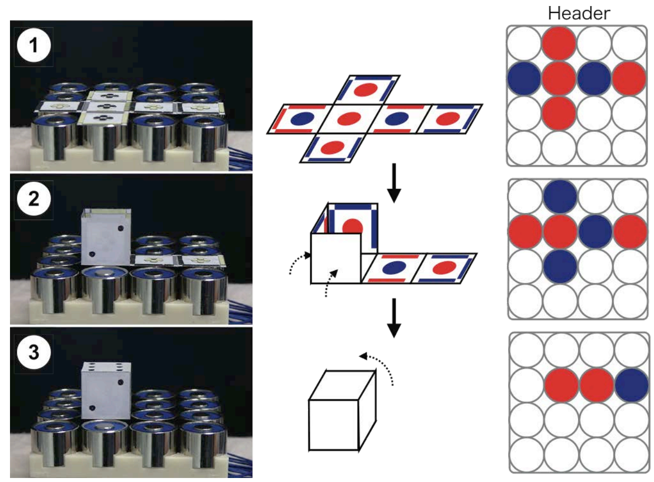

Figure 18. Electromagnet control with order of paper folding and magnetic pattern design.

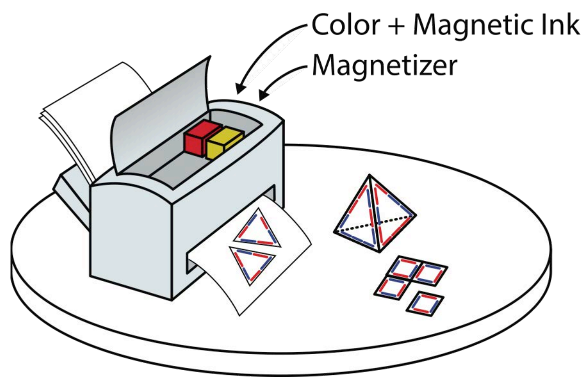

Figure 19. Future image of FluxPaper printing with magnetic ink tank and magnetizer head to print a magnetized magnetic layer on the usual paper.

believe that this ecosystem can cover the entire design of FluxPaper material and will be of great help for personal creation. In the future, according to applications regarding the ability to perform on speed and portability of FluxPaper, soft plastic may be proposed by collaborating with other actuators and materials including SMA enabling several functions for paper motion and the ability to realize geometric motions.

LIMITATIONS

The current method to produce FluxPaper is not automated. However, for the vision of printable FluxPaper, we are considering a way to use thermoplastic resin. Generally, a magnet has a limit temperature to lose magnetic strength, but this issue can be solved by magnetizing after printing the magnetic layer with thermoplastic resin. UV-curable resin based magnetic ink is another possible approach.

The thickness of magnetic layer limits the magnetic force accordingly. Large-scale paper relatively reduces the magnetic force from the magnetic layer. We think a size of around a Post-it® note (76 mm x 76 mm) is appropriate to demonstrate the applications. In addition, FluxPaper in our current applications has double paper layers (0.1 mm each) and one magnetic layer (0.1 mm each) to simplify the production process (see Figure 4). Therefore, an attractive force of stacked FluxPaper becomes weak due to the increment of paper thickness. This limitation will also be resolved by using above-mentioned automated printing system. To establish an effective printing and magnetizing patterns for various applications is also important.

In applications, we succeeded in implementing the self-folding FluxPaper with controlling electromagnets. However, there are several limitations. The size and strength of the magnetic field limit the size of the electromagnets. By using smaller and stronger electromagnets, we can control self-construction precisely. That also can be said for card magic application. The expression of pattern is not much, limited to under eight papers in one task because of the numbers of the header. We can easily manipulate many more papers by increasing the number of electromagnets or using "dithered" magnetization patterns.

RELATED WORKS

FluxPaper has four types of field of HCI research: novel interaction and actuation through magnetism, shape-changing and programmable materials, paper interaction and active paper, and printing and designing paper as a functional material.

There are several approaches to using magnetic power to HCI applications. ZeroN [14] is presented as a tangible user interface that is powered by magnetic levitation. Triangles [6] are also a tangible interface, but the magnet is used for connecting each block of hardware to help a user construct the complex structure by hand. Actuated workbench [17] is a tabletop interface that creates magnetic attraction through electromagnets. Madgets [25] also achieved tabletop interaction actuated by magnetic force. Two sets of research show examples of leveraging magnetic power to make the material active in the spatial interface. Programmable Blobs [24] is a shape-changing material reacting to changes in the magnetic field.

Using other methods, there are still several ways to design shape-changing materials. For example, PneUI [26] is soft composite interface actuated by air pressure. These two materials are designed for special applications. However, there are other bodies of research on actuating paper. POPAPY [27] uses heat-shrinkable tubes on the paper, shrinking when the paper is placed in a microwave. Bridging book [4] is a sensing idea using a compass sensor to count the page numbers of a book. The magnet is installed in each page. However, the thickness of the book becomes large due to the neodymium magnet. Our approach changes the paper from general everyday material to active and programmable material without losing the appearance and function of the paper. The input method to use the metaphor of paper is also achieved by [5, 7, 13].

Other types of paper interaction have been proposed. Saul et al. describe several types of paper designs for actuation and interactive systems by instructing with LED lights for folding [7], and with the SMA to actuate the paper [12, 18, 19, 21, 28]. Though ideas of using SMA tend to use wired designs for the paper, Koizumi et al. [12] consider a wireless method for moving the paper with SMA heating by laser irradiation. In addition, there is the idea of using power transmission via electromagnetic induction on the paper material [28, 29]. Paper material research by Figueiredo et al. [3] changes the shape of paper by heat caused by electricity and makes it possible to build an executable robot structure. As with SMAs on paper, these ideas require heat to change the state of the material to actuate or shape change. FluxPaper does not require heat of electricity on the paper because the magnetic layer reacts to external magnetic fields.

As with FluxPaper, printing or implementing functions on paper is a common way to realize new interactive technology. Paper Generators [9] are designed for acquiring electricity from paper rubbing; Anabiosis [23] and Electric origami [8] have the function to change the color of paper. Pulp-based computing [2] shows the vision of paper-printed sensors and actuators. Klemmer et al. [11] achieved a tangible interface for designers by providing paper-based affordance. Making or implementing the circuit is proposed in much research [2, 15, 20, 22], and the idea of printing with Ag ink [10] makes paper a precise circuit of computer assisted design. Our idea shares the same concept of printing functions and calculates efficient designs for paper media.

CONCLUSION

We have made contributions in producing, designing, and manipulating strong magnetized paper with efficient patterns, and achieved a new modality of paper interaction powered by a magnetic flux generated from the movable or handheld electromagnet apparatus controlled by a computer. By showing Self-alignment and Computer-actuated instances, we have demonstrated the invention of active paper and its fast, powerful, and precise manipulation.

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