FieldSweep: A 2D Tracking System With Embedded Magnets and a Smartphone

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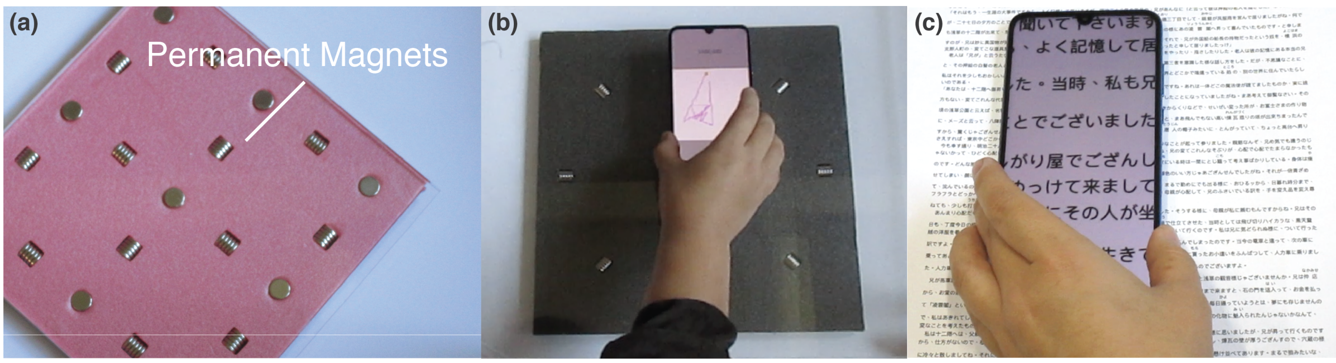

Figure 1: (a) A magnets arrangement used for FieldSweep system. (b) Tracking. (c) Application example (Magnifying glass).

ABSTRACT

In this paper, we propose FieldSweep, a tracking method on a plane using only permanent magnets and a smartphone. This method estimates the position of a magnetic sensor on a plane using the magnetic fields of permanent magnets placed at an appropriate pattern. The magnetic sensor is a built-in one in a smartphone. Since the planar side consists of only magnets and a plate for fixing the magnet, no power supply or electronic components are required for the system. In this paper, we report the necessary conditions for tracking, present the implemented prototype, and discuss possible future developments and applications.

CCS CONCEPTS

• **Human-centered computing → Ubiquitous and mobile computing**.

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KEYWORDS

Interaction, Magnetic-field Sensing, Smartphone.

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1 INTRODUCTION

Our lives are filled with information. Information provided in public places, such as station signs, maps, school bulletin boards, and billboards, is often printed on paper or boards and displayed on a flat surface. In recent years, the price of LCDs and projectors has decreased, and more and more information is presented via digital signage. For example, many information boards and vending machines with touch panels have been installed in cities. In addition to touch panels, there are projectors on the market that simultaneously detect movement and project images.

Many of these interactive systems are based on the use of hand and finger movements. Therefore, there is a growing demand for technology to detect the motion of objects on a plane. In the past, capacitive touch panels, cameras, and infrared sensors were mainly used for this detection. However, they are expensive and require a power source, making it difficult to deploy them ubiquitously.

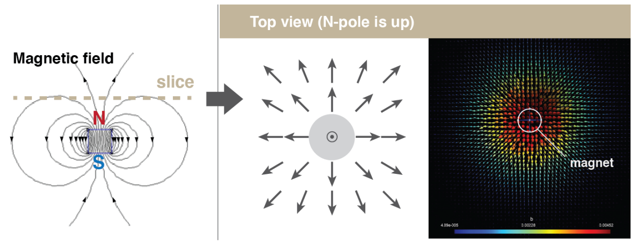


Figure 2: Front view of ϕ10mm×H10mm magnet and its magnetic flux (left). If we slice it and see this vector field from the top, we can see the vectors as an illustration (middle) and a graphics simulation (right).

In this paper, we propose FieldSweep, a tracking method on a flat surface using only permanent magnets and a smartphone. This method tracks the position of the smartphone as it slides above the permanent magnets (Figure 1). The basic mechanism is to measure the magnetic field created on the plane by the permanent magnets using a three-axis magnetic sensor on the smartphone, and to estimate the relative position to the magnets from the three-dimensional vector of the measured magnetic field lines. Since only a permanent magnets and a fixing plate, such as an acrylic plate, are used on the plane side, no electronic components or power supply are required. In addition, since the triaxial magnetic sensor is a standard feature of smartphones, there is no need to add components or sensors to the smartphone side.

Permanent magnets have been studied for a long time as an input tool because they do not require a power source and the strength and direction of the magnetic field can be used to detect distance and motion. However, no attention has been paid to the pattern of the magnetic field in two dimensions created by permanent magnets. In addition, there are some studies on tracking from the motion sensors of smart phones and smart watches, and the optical sensors attached to smartphones. However, it is impossible to detect the absolute coordinates. In our method, the magnetic field pattern allows us to detect absolute coordinates within a certain range.

In this paper, we report the necessary conditions for 2D tracking using permanent magnets, and present a prototype implementation. Possible future developments and applications are also discussed.

2 TRACKING PRINCIPLE

A magnet generates a magnetic field around it. This is a three-dimensional vector field centered on the magnet; if a three-axis (X, Y, Z) magnetometer is placed in this field, the three-dimensional magnetic vector at that point can be measured. Figure 2 shows the magnetic vector field generated by a ϕ10mm×H10mm cylindrical magnet on a plane 30mm away from the N-pole side.

In FieldSweep, we first store the magnetic vector field data of the plane above the magnets. The magnets are configured in a specific pattern. The data is a two-dimensional array of three-dimensional vector values. Next, we construct the actual magnet configuration and place a smartphone on the plane at a distance corresponding to the simulation. Then we measure the directional vector of the magnetic field using the built-in three-axis magnetometer. The angle of the measured vector is compared with the simulated data. The location of the data with the closest angle is considered as the position of the magnetometer. The closeness of the angle is indicated by the cosine similarity between the simulated vector and the measured one.

3 MAGNETIC FIELD DESIGN

In our method, the sensor is calibrated with the ambient magnetic field because it constitutes noise in the measurement. The ambient magnetic field is measured before tracking starts, and its value is subtracted from the measured value during tracking. Therefore, the intended magnetic field by the magnets should be sufficiently larger than the ambient magnetic field, to perform stable measurement. We perceived that an approximately 2 times stronger magnetic field is needed for stable tracking through our study. Thus, it is desirable that the magnets are arranged so that the magnetic field intensity is large enough all around the tracking field.

Furthermore, the magnetic vectors must be in different directions at each location to uniquely determine the position. To achieve stable tracking by this method, the magnets are placed with these two points in mind.

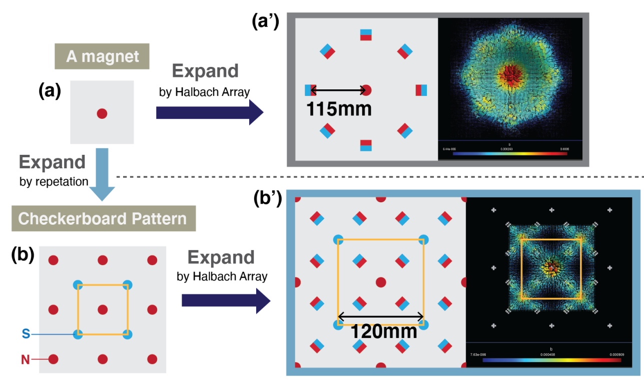


Figure 3: Magnet patterns proposed in this method.

In order to expand a single magnet's (Figure 3(a)) magnetic field pattern to a large area, we considered two types of extension method. One method is the repetitive expansion shown in Fig.3(b) and (b'). By arranging the magnets in a checkerboard pattern with the N and S poles facing forward, the magnetic field area that can be measured with a smartphone can be extended to a larger area (Figure 3(b)). Here, the yellow square in the figure is one unit, and the magnet arrangement is repeated left to right, and up and down. Hereinafter, this unit is referred to as a repetitive unit. The repetitive units have exactly the same magnetic field pattern, so the magnetic vector can be unique only in one repetitive unit. Therefore, the absolute position can only be estimated within this one unit.

Furthermore, we assumed that we can use a magnet array called a Halbach array to expand the range of the magnetic field further. The one-dimensional Halbach array is illustrated in Figure 4. By alternating magnets with N and S poles facing up and down, a magnetic field of equal strength is generated at the top and bottom

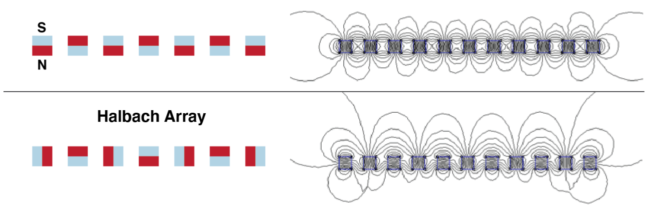


Figure 4: The upper figure is an array with the N and S poles alternately facing upward, and the lower figure is a one-dimensional Halbach array.

surfaces (Figure 4 top). On the other hand, in the Halbach array, a horizontal magnet is inserted between each magnet (Figure 4 bottom). The magnetic field on the top surface is enhanced by the interference of the vertical and horizontal magnets.

We used this idea to expand a magnetic field further, for Fig.3(a) and (b) each. They are shown in Fig.3(a') and (b'), respectively. In the following, we refer to them as pattern (a') and pattern (b'), respectively.

In pattern (a'), a single magnet's magnetic field was enlarged to a circular pattern. The magnets are placed horizontally to strengthen the magnetic field on the upper surface, using the idea of the Halbach array.

In pattern (b'), we used the Halbach array again to expand the size of one repetitive unit of the checkerboard pattern. A horizontal magnet was placed between each of the upward-facing magnets. This arrangement generates a sufficient magnetic field on the tracking surface even when the magnet spacing is widened. As a result, the repetitive unit range can be large, compared with a simple checkerboard pattern.

4 IMPLEMENTATION

Based on the magnet arrangements discussed in the previous section, we developed a prototype system that uses magnets arranged in the shapes of pattern (a') and pattern (b'). As shown in Figure 3, the distance between the central magnet and the surrounding magnets in pattern (a') is 115mm, and the repetitive unit of the magnets in pattern (b') is 120mm.

4.1 Type and Size of Magnets

In this research, we aim to realize inexpensive devices that can be ubiquitously used in daily life and public places. On the other hand, the use of strong magnets will enable position detection over a wider area. Therefore, we used neodymium magnets, which are commonly available. Ferrite magnets and rubber magnets are less expensive, but their magnetic force is weak. In this prototype, we used five disks of neodymium magnets of 13mm×2mm (25 yen without tax). The cost per unit of magnets is about 130 yen; cheap enough to deploy in various everyday situations.

4.2 Distance Between Magnet and Sensing Surface

The position of the sensing surface relative to the magnet, i.e., the position where the three-dimensional magnetic vector field is sliced, affects the intensity of the measured magnetic field. This distance is also the thickness of the actual system. In this case, the distance for pattern (a') is 40mm and for pattern (b') is 50mm. This is because the measurement stops when the smartphone sensor is operated in a powerful magnetic field. This phenomenon is also described in section8.

4.3 Vector Field Data Generation

To generate vector data of the magnetic field, we used ONELAB. ONELAB is an open-source finite element solver interface. Gmsh, mesh generation software, and GetDP, a mesh solver, were used [8]. The data were generated at 2mm intervals.

4.4 Measurement of Magnetic Data

The magnetic vectors are measured using a three-axis magnetic sensor mounted on a smartphone. We used a Huawei P30 lite (Android OS), and the measurement was performed at 60Hz. The moving-average filter smoothed the measurement to reduce the noise caused by the sensor's measurement error. We averaged 30 data points over 0.5 seconds and used the value as the most recent magnetic data measurement.

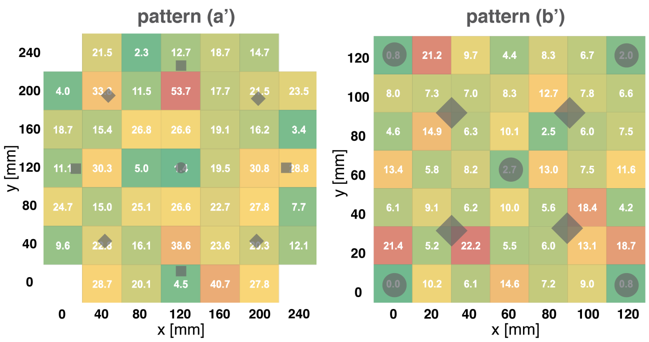
Depending on the magnets' arrangement, there are areas where the magnetic field is weak, and the geomagnetic field's influence cannot be ignored. Therefore, we needed a calibration to eliminate the ambient magnetic field's influence before starting the measurement. For this calibration, we kept the smartphone in the same position and direction as during the measurement for one second before starting the measurement. The values collected here were averaged and subtracted from the sensor's value at the time of tracking.

4.5 Position Detection Program

The application that performs position detection and verifies its operation was implemented on the Unity platform using C#. This program detects the position of the smartphone using the following procedure.

When the user places the smartphone on the sensing surface, the system's program measures the magnetic field vector, compares it with the magnetic field direction vector information prepared in advance, and detects the smartphone position. Furthermore, in the case of a magnet configuration with a repeating magnetic field pattern, as in pattern (b'), an algorithm is needed to determine in which repeating region the smartphone is placed. We used the distance between the most recent location and the candidate point to determine if the smartphone is in a repetitive region.

The first step of the positioning program is to estimate the initial position. For this purpose, it first extracts multiple vectors from the whole pattern that have a similarity greater than a certain threshold to the detected magnetic field vectors, and then makes a group of guess positions. When the next magnetic field vector is detected, the points within a certain distance from the previous one with vectors above a certain threshold are selected as a new set of



	(a')	(b')
Min.[mm]	1.4	0.0
Max.[mm]	53.7	11.1
Avg.[mm]	27.6	22.2
Avg.[%]	12	9

Figure 5: Results of accuracy evaluation. The average error [mm] for each grid point is shown. Pattern (a') on the left and pattern (b') on the right. The black figures show the magnet position. The table shows the minimum, maximum, and average errors [mm] and error rate [%] for each pattern.

guess positions. When the positions of the extracted vectors have been determined to some extent, the center of the group of guess positions is set as the initial position. After the initial position is estimated, we continue to measure the magnetic field vectors and compare the magnetic field data within a certain distance from the previous guessing points to find similar guessing points and set the center of the guessing points as the new position. If there are similar vectors far away from each other, we select the nearer one from the previous position as the estimated position.

5 EVALUATION

We conducted an experiment to evaluate the accuracy of the tracking for patterns (a') and (b').

We prepared a grid of points with 40mm spacing for pattern (a') and 20mm spacing for pattern (b') from edge to edge of the board, and measured the distance between the estimated position and the actual position at each point. This was done for both patterns. However, the four corners of pattern (a') was excluded from the measurement because the magnetic field was circularly enlarged and the magnetic field intensity of the four corners were weak.

First, the position of the magnetic sensor in the smartphone was checked. When the S-pole of the magnet is placed perpendicular to the screen of the smartphone, the compass needle of the three-dimensional compass application [1]is placed perpendicular to the screen. When the S-pole of the magnet was placed perpendicular to the screen of the smartphone, the position of the sensor was determined to be the position where the compass needle was perpendicular to the screen.

Next, we assigned a random order to each grid point so that the order of measurement of the grid points would be random. Then, we started the application and estimated the initial position. The initial position was arbitrarily selected from the measurement target area. After the initial position estimation, the smartphone was moved so that the sensor of the smartphone was positioned directly above the grid point to be measured, and the position was estimated. The position was estimated by moving the smartphone so that the sensor of the smartphone was positioned directly above the grid point to be measured. This was done continuously for all grid points according to the measurement order. The above procedure was carried out five times in total. This evaluation was conducted by the author.

The error (the distance from the original coordinates to the measured point) averaged over all trials for each grid point is shown in Figure 5. In pattern (a'), the average error over the entire area was 27.6mm, and in pattern (b') it was 11.1mm. The errors for one side of the measurement area were 12% for pattern (a') and 9% for pattern (b'), which means that the position could be detected with an error of about 10% each.

There are several reasons for these errors. The first is that there are several similar vectors around a point. This method determines the position based on the similarity of the vector angles. When similar vectors exist at distant locations, such as the four corners of pattern (b') (all right above the S-pole), the method judges the closer one as the current location based on the distance from the previous estimated location. However, there are also similar vectors at close distances to each other. In this case, whether the correct vector is selected depends on the degree of discrepancy between the simulation and the actual measurement. This discrepancy is partly due to the sensitivity of the sensor. In addition, there is an error caused by the use of the finite element method in the simulation.

In addition, when the magnetic field is weak, the deviation becomes more pronounced. If the magnetic field is weak, it becomes more pronounced, because the vector is smaller than that of a strong magnetic field, and the angle error becomes larger. Therefore, if there are many areas where the magnetic field is weak, as in pattern (b'), the error is likely to be large.

6 APPLICATIONS

By tracking the position of the smartphone, the display of the smartphone can be used as a moving window frame on the board. Such an interaction has already been proposed in other research [11] [5] [6] [14].

In this study, we implemented an application of a magnifying glass. This application was implemented on Unity as well as the aforementioned verification program. In this application, tracking is performed on a piece of paper on which pictures and letters are written, and only the part of the image identical to that of the paper that is enlarged at the sensor's position is shown on the display, thus presenting an interaction as if a part of the paper in the real world were enlarged and displayed (Fig.1(c)). The same system can be used as a live translation application.

We believe that our system can also be applied to other applications, such as a system that displays images from a camera on the other side of a wall or door, so that only the display area becomes

[1]https://play.google.com/store/apps/details?id=com.plaincode.magnetmeter

see-through. In addition, since our system can be used with multiple people at the same time, it can also be used for interactions such as multiplayer games.

7 RELATED WORK

7.1 Input and Tracking Using Magnetism

Various technologies have been developed for tracking and input using magnets. In particular, permanent magnets, which do not require a power source and are inexpensive, are often used in human-computer interaction (HCI) research because they are easy to use and readily available. Chen et al. estimated the three-dimensional motion of a magnet attached to a thumb from the input of two magnetic sensors attached to another finger[1]. Liang et al. used a planar array of Hall elements and used their input to determine the magnets' motion on a device[7]. TRing[17], like our method, fixed a permanent magnet and estimated the 3D position around the magnet based on its magnetic field and the values from a 9-axis inertial measurement unit (IMU) attached to the finger.

Besides, there is research on detecting indoor locations based on fingerprints of environmental magnetic fields such as geomagnetic fields measured by smartphones[12, 15].

These studies used a single magnet or an environmental magnetic field, and no paper has discussed magnetic fields intentionally created by multiple magnets. This study uses multiple-magnet configurations to achieve scalable and dense tracking compared with these studies.

7.2 Two-dimensional Tracking

Various techniques for two-dimensional tracking have been studied.

Position detection using optical emitters and sensors has been studied for a long time and is highly accurate and scalable [9]. Methods using cameras and image processing have also been widely developed[13]. The capacitive method is a highly accurate tracking method, especially for detecting a finger's or stylus's contact with the panel, and is often seen in daily life [2, 10]. These methods require a power supply and installation cost.

Some methods use hand-held machines or sensors for tracking, like our method. For example, mechanical[11] and optical[3] mouse methods have been proposed for interaction to detect object movement. However, since these methods can only estimate relative movement, the initial position must be specified. Leigh et al.[6] and Yeo et al.[16] used an LCD, and Xiao et al.[14] used a capacitive touch panel to track mobile devices on a planer surface. Furthermore, the Anoto method uses a small camera attached to a pen to read a special pattern and determine the position on a plane[4]. Our method does not require special patterns for the surface and only requires a smartphone as the handheld machine.

8 LIMITATIONS AND DISCUSSION

In this paper, we used one type of smartphone for implementation. The characteristics of the magnetic sensor and the operating program differ depending on the smartphone and the operating system (OS). Since the smartphone's magnetic sensor is installed to read the geomagnetic field, it sometimes behaves abnormally when it reads a strong magnetic field. In the process of prototyping, we found that some models stopped outputting values when the sensor saturated. In addition, there was a smartphone whose value fluctuated after the sensor was saturated, probably due to the magnetization of the component when placed near a magnet.

The smartphone used in this study also experienced a crash of the application when continuously measuring magnetism above a certain strength. Therefore, space was created between the magnet and the sensing surface to prevent too strong a magnetic field from being applied. In the future, we would like to consider a magnet arrangement where the strong magnetic field is not concentrated but distributed widely.

The magnetic field vector's direction read by the magnetic sensor on the smartphone changes depending on its posture. In this implementation, we adopted a method in which the orientation of the smartphone is fixed. We believe that the accelerometer can measure the direction of gravitational acceleration on the smartphone. The smartphone's tilt could be automatically corrected if the application is limited to vertical planar surfaces such as bulletin boards and posters in public places.

The error between the simulation and the measurements is the sum of the tilt of the smartphone, the error of the sensor, and the error of the simulator. In addition, the tracking error is related to the similarity of nearby vectors. The more similar vectors are clustered nearby, the larger the distance error is likely to be. In the future, we would like to evaluate patterns in terms of the direction of these vectors.

Currently, only the angle is used to determine the similarity of the vectors. This is because there is a difference between the magnetic field strength of the simulation and that measured by the smartphone due to problems such as saturation of the smartphone. However, these can be calculated and calibrated. Therefore, we would like to consider the use of intensity in addition to angle in the future.

As mentioned in section 4, we need environment magnetic field calibration every time before the tracking. This may degrade the system's usability.

In this study, we evaluated each point on the grid. In the future, we would like to evaluate the continuous trajectory as well.

With this method, it is not possible to determine which repetitive pattern we are in. Therefore, a different process is needed to determine it. For example, we need to start tracking from a specific position.

9 CONCLUSION

This paper presents FieldSweep, a two-dimensional tracking method using only a smartphone and inexpensive permanent magnets. This method requires no external power supply, no electronic components, and no attachments to the smartphone.

We would like to improve the magnet layout, the position estimation algorithm, and the application in the future. In particular, we believe that there is room for improvement in magnet placement, such as placing thin magnets widely and thinly, and mixing magnets of different size and type.

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