A Smartphone Short-Range Path Estimation Method using Spinning Magnet Marker

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Abstract—In recent years, various location information has been used with a spread of smartphones. Our purpose is to estimate a three-dimensional position of a pedestrian's smartphone with an error of several centimeters and to recognize people's behavior patterns. In addition, we will provide new services based on the three-dimensional position. We proposed a positioning method which can be used to a smartphone based on a dynamic magnetic field generated by a Spinning Magnetic Marker(SMM). The SMM is a device that spins a powerful magnet with a motor and generates a dynamic magnetic field which can be detected by a smartphone. In this paper, we derive approximate equations of a dynamic magnetic field that a moving smartphone receives from the SMM. Then, we propose a method to estimate an initial position and velocity of a smartphone by curve-fitting the measured magnetic field by approximate equations. Our evaluation resulted that the short-range path of a smartphone moving at a uniform linear motion with an error within 5.4cm when the distance is within 1m from the SMM.

Index Terms—smartphone, magnetic field, positioning, pathestimation

I. INTRODUCTION

Recently, an importance of location information has increased with the spread of smartphones. Our purpose is to estimate a three-dimensional position of a smartphone with an error within several centimeters. In addition, we would like to recognize behavior patterns of people, and targets of their interest. These information based on a three-dimensional position of a smartphone will provide new services. For example, it is possible to know a tendency of a customer in a store from a customer's route or interested products. Then, based on that tendency, store manager can replace arrangement of products, and give information for customer to promote their products.

Positioning methods based on a dynamic magnetic field [1] have several advantages. In these methods, a three-dimensional position of a device can be estimated with an error of from several millimeters to several centimeters [2] [3]. Furthermore, these methods have high permeability [4] [5] compared with other methods. However, it is difficult to apply these positioning methods based on a dynamic magnetic field to

a smartphone. This is because a sampling frequency of a smartphone is several tens of hertz, whereas these methods use a dynamic magnetic field with several kilohertz [6] [7].

We have developed a Spinning Magnetic Marker(SMM), and proposed a positioning method based on a dynamic magnetic field which can be applied to a smartphone [8] [9]. The SMM is a device that spins a powerful magnet with a motor and generates a dynamic magnetic field having a specific frequency. Since the magnet is used to generate magnetic field, a cost of generating magnetic field is low compared with a method using coils. Moreover, since a frequency of the magnetic field is several tens of hertz, it is possible to detected even at a sampling frequency of a smartphone.

Takeshima et al. studied a method to detect a passenger with a smartphone using SMMs [8]. They also studied a twodimensional smartphone positioning method using an SMM. In addition, we previously studied a three-dimensional positioning method of a stationary smartphone using an SMM [9].

Our purpose in this study is to estimate a short-range path of a moving smartphone. We estimate an initial position of a smartphone moving at a uniform linear motion with a mean error within 5.4cm, and estimate velocity with a mean error within 0.01m/s.

II. ESTIMATION METHOD

A. DYNAMIC MAGNETISM EQUATIONS

In order to estimate a short-range path of a moving smartphone, we derive approximate equations of a dynamic magnetic field generated by an SMM. From our previous work, we define a relationship between a dynamic magnetic field generated by the SMM and a three-dimensional position of a smartphone as shown in Fig.1. When we approximate a magnetic field of a magnet as that of a magnetic dipole, the relationship are derived as following equations with the threedimensional polar coordinates.

$$H_x = H_r \cos\varphi \cos\psi + H_\varphi \sin\varphi \cos\psi_\varphi \cos\theta_\varphi \qquad (1)$$

$$H_y = H_\varphi \sin\varphi \cos\psi_\varphi \sin\theta_\varphi \tag{2}$$

$$H_z = H_r \cos\varphi \sin\psi + H_\varphi \sin\varphi \sin\psi_\varphi \tag{3}$$

In these equations,

$$\cos\varphi = \cos\psi\cos\omega t \tag{4}$$

$$\cos \theta_{\varphi} = \sin \omega t \frac{\cos^2 \psi \sin \omega t \cos \omega t}{\sqrt{1 - \cos^2 \psi \cos^2 \omega t (1 + \sin^2 \psi)}}$$
$$- \cos \omega t \sqrt{1 - \frac{\cos^4 \psi \sin^2 \omega t \cos^2 \omega t}{1 - \cos^2 \psi \cos^2 \omega t (1 + \sin^2 \psi)}} (5)$$
$$\cos \psi_{\varphi} = \sqrt{\frac{1 - \cos^2 \psi \cos^2 \omega t (1 + \sin^2 \psi)}{1 - \cos^2 \psi \cos^2 \omega t}} (6)$$

From these equations, we derive approximate equations of a magnetic field that a moving smartphone detect from the SMM.

We assume that a smartphone moves in a two-dimensional plane for this time. Substituting $\psi = 0^{\circ}$ into (1)(2)(3) yields magnetic field equations as follows.

$$H_x = H_r \cos(\theta - \omega t) \cos\theta - H_\varphi \sin(\theta - \omega t) \sin\theta \qquad (7)$$

$$H_y = H_r \cos(\theta - \omega t) \sin \theta + H_\varphi \sin(\theta - \omega t) \cos \theta \qquad (8)$$

$$H_z = 0 \tag{9}$$

Since we approximate a magnetic field of a magnet as that of a magnetic dipole, we assume that H_r, H_{φ} are inversely proportional to the distance r^3 .

$$H_r = \frac{A}{r^3} \tag{10}$$

$$H_{\varphi} = \frac{B}{r^3} \tag{11}$$

Then, substituting (10)(11) into (7)(8)(9) yields the following equations.

$$H_x = \frac{A}{r^3}\cos(\theta - \omega t)\cos\theta - \frac{B}{r^3}\sin(\theta - \omega t)\sin\theta \qquad (12)$$

$$H_y = \frac{A}{r^3}\cos(\theta - \omega t)\sin\theta + \frac{B}{r^3}\sin(\theta - \omega t)\cos\theta \qquad (13)$$

Equation (12)(13) are approximate equations of a magnetic field measured by a moving smartphone in a two-dimensional plane. Furthermore, we derive an equation of a magnetic norm from these equations as follows.

$$H = \sqrt{\frac{B^2}{r^6} + \frac{A^2 - B^2}{r^6} \cos^2(\theta - \omega t)}$$
(14)

By substituting functions representing a smartphone shortrange path into r, θ in (14), approximate equation of a magnetic norm in that short-range path is derived.

We assume that a smartphone moves with uniform linear motion. Fig.2 shows a smartphone short-range path. In this figure, an initial position of a smartphone is denoted as x_0, y_0 , and velocity in the y-axis direction is denoted as v_y . At this





Fig. 2. Smartphone short-range path

time, the distance r and the azimuth angle θ in (12)(13) can be written as

$$r = \sqrt{x_0^2 + (y_0 + v_y t)^2} \tag{15}$$

$$\theta = \arctan\left(\frac{y_0 + v_y t}{x_0}\right) \tag{16}$$

We perform the following process to estimate a shortrange path of a smartphone. We perform curve fitting to a measured magnetic data using (14)(15)(16) with an initial position x_0, y_0 , and velocity v_y as fitting parameters. We regard these fitting parameters obtained by curve fitting as a estimated short-range path of a smartphone.

However, when a short-range path of a smartphone is estimated from a magnetic norm, it is difficult to determine a direction of a smartphone. Therefore, we use the y-axis component of a magnetic field. When a smartphone is closest to the SMM, if $v_x > 0$, the y-axis component changes from positive to negative according to (13). By using the y-axis component change, a direction of a smartphone is determined.

B. COMPARISON WITH SIMULATION

In order to evaluate approximate equations derived in II-A, we conduct a comparison with a simulator. We use a magnetic field analysis solver Qm¹. A shape of a magnet is set into a rectangular parallelepiped having a width of 2.22cm, a height of 2.22cm, and a depth of 3cm so as to have the same volume as that of the magnet. The BH curve has a residual magnetic flux density of 14, 300G and a coercivity of 10,000Oe. Shortrange path of a smartphone is $(x_0, y_0) = (-1m, 0.5m)$, $v_x = 0.1m/s$, and $(x_0, y_0) = (-1m, 1m)$, $v_x = 0.1m/s$ in Fig.2.

Fig.3 and Fig.4 show a comparison of a magnetic field by simulation and by approximate equations (12)(13). In

¹http://www.slock.co.jp/Qm3/index.html (in Japanese)



Fig. 3. Comparison of magnetic field by simulation and by approximate equation $(x_0, y_0) = (0.5m, -1m), v_y = 0.1m/s$



Fig. 4. Comparison of magnetic field by simulation and by approximate equation $(x_0, y_0) = (1m, -1m)$, $v_y = 0.1m/s$

these figure, the black line and the gray line represent an absolute value of a difference between the simulation result and the approximate equations for the x-axis and the y-axis, respectively. As shown in Fig.3 and Fig.4, the x-axis component of the approximate equation is slightly larger than the simulation result around time t = 10, however it can be seen that the overall agrees well.

C. ENVIRONMENTAL MAGNETIC FIELD INFLUENCE RE-DUCTION

A measured magnetic field is affected by an environmental magnetic field such as a geomagnetic field, and a magnetic field in a building. To reduce the influence of an environmental magnetic field, we perform the following environmental magnetic field influence reduction process.

First, we divide a measured magnetic field for each magnet spinning cycle. Then, an average of a magnetic field is calculated for each divided magnetic field, and the obtained average is subtracted from the original magnetic field data. Finally, each divided magnetic field data is integrated into one.

Fig.5 shows measured the x-axis magnetic field before the environmental magnetic field reduction process and after that process. As will be described later, this data was measured on path2 in Fig.6(b). A mean value of a magnetic field denoted a blue line is far away from 0μ T because of the influence of the



Fig. 5. x-axis magnetic field before noise reduction and after(left vertical axis: blue line, right vertical axis: red line)



environmental magnetic field, and the oscillation is different from the simulation result of Fig.4. On the other hand, a mean value of a magnetic field denoted a red line is almost equal to 0μ T, and the oscillation is close to the simulation result of Fig.4.

III. EVALUATION EXPERIMENT

A. EXPERIMENT PREPARATION

To evaluate the smartphone short-range path estimation, we made a belt conveyor. Since metallic materials become magnetized, we created frames and pulleys by plastic using a 3D printer. In addition, we used screws made of polycarbonate, and nuts made of vinyl chloride. Fig.6(a) shows the experiment situation using belt conveyors. In order to reduce an influence of a magnetic field from a floor, the SMM was set on a plastic base of about 1m in height, and the belt conveyor was set on desks. Moreover, the SMM was set so that the magnet height was the same as the height of the smartphone.

We set the magnet spinning cycle of the SMM to 1Hz and the angle at which the N pole of the magnet is in the positive direction of the x-axis is defined as the azimuth angle 0°. We used an iPhone 6 Plus for the experiment. Furthermore, a sampling frequency of a magnetic sensor was set to 100Hz. Fig.6(b) shows three short-range paths of a smartphone estimated in the experiment. Each short-range path has the following initial position and velocity, path1: $(x_0, y_0) =$ $(0.5m, -1m), v_x = 0.1m/s, path2:(x_0, y_0) = (1m, -1m),$ $v_x = 0.1m/s, and path3:(x_0, y_0) = (1.5m, -1m), v_x =$





TABLE I RESULTS OF SHORT-RANGE PATH ESTIMATIONS

	Path1			Path2			Path3		
	cm		m/s	cm		m/s	cm		m/s
	x_0	y_0	v_x	x_0	y_0	v_x	x_0	y_0	v_x
True Value	50	-100	0.1	100	-100	0.1	150	-100	0.1
Mean Error	3	4.6	0.01	0.4	5.4	< 0.01	9.8	17.3	0.03
Standard Deviation	< 0.1	1.1	< 0.01	0.5	3.2	< 0.01	2.1	27.4	0.04

 $0.1 \mathrm{m/s}$. For each experiment, the measurement time was 20 seconds and the measurement was performed 5 times.

B. EXPERIMENTAL RESULT

Fig.7 shows the results of the experiment. In this figure, black line represents an approximate curve plotted using the fitting parameters. Fig.7(a)(b) show the approximate curve coincide with the measured magnetic field for path1 and path2. Fig.7(c) shows the approximate curve deviates from the measured magnetic field for path3. The measured magnetism is affected about 3μ T due to the environmental magnetic field as shown Fig.5. As shown Fig.7, the amplitude of the magnetic norm is about 1μ T, therefore it is thought the influence of the environmental magnetic field is not sufficiently reduced. The table I shows the estimation accuracy. From this table, the estimation accuracy tends to decrease with the distance from the SMM. This table also shows that a mean error of an initial position is within 5.4cm at the closest distance up to 1m.

IV. CONCLUSION

In this research, we proposed a smartphone short-range path estimation method using an SMM. First, we derived approximate equations of a magnetic field detected by a moving smartphone. Next, we proposed a method to estimate the short-range path by curve fitting with the approximate equations. As a result of experiments in a case of that a smartphone is moving with a uniform linear motion, we estimated a initial position as a mean error 5.4cm, and velocity as a mean error 0.01m/s within the distance 1m from the SMM. From these results, in case of a uniform linear motion that the closest distance from the SMM is within 1m, we achieved three smartphone short-range paths estimation with an accuracy within several centimeters. As future works, we would like to extend this method to a more complicated short-range path, for example, a bended short-range path, and non-uniform motion. Other future work is to expand this method to estimate a short-range path of a smartphone with an arbitrary pose. Furthermore, we would like to consider a smartphone short-range path estimation method using multiple SMMs.

ACKNOWLEDGEMENT

This work was supported by JSPS KAKENHI Grant Number JP17H01762.

REFERENCES

- Eugene Paperno, Ichiro Sasada, and Eduard Leonovich. A New Method for Magnetic Position and Orientation Tracking. *IEEE Transactions on Magnetics*, 37(4):1938–1940, 2001.
- [2] Antonio Moschitta, Alessio De Angelis, Marco Dionigi, and Paolo Carbone. Analysis of Simultaneous 3d Positioning and Attitude Estimation of a Planar Coil using Inductive Coupling. In Proceedings of Instrumentation and Measurement Technology Conference (I2MTC), 2017 IEEE International, 1–6, 2017.
- [3] Guido De Angelis, Alessio De Angelis, Antonio Moschitta, and Paolo Carbone. Comparison of Measurement Models for 3d Magnetic Localization and Tracking. *Sensors*, 17(11):2527, 2017.
- [4] Joerg Blankenbach, Abdelmoumen Norrdine, and Hendrik Hellmers. A Robust and Precise 3d Indoor Positioning System for Harsh Environments. In Proceedings of 2012 International Conference on Indoor Positioning and Indoor Navigation (IPIN), 1–8, 2012.
- [5] Gerald Pirkl, Peter Hevesi, Jingyuan Cheng, and Paul Lukowicz. mbeacon: Accurate, Robust Proximity Detection with Smart Phones and Smart Watches using Low Frequency Modulated Magnetic Fields. In Proceedings of the 10th EAI International Conference on Body Area Networks, 186–191, 2015.
- [6] Gerald Pirkl and Paul Lukowicz. Robust, Low Cost Indoor Positioning using Magnetic Resonant Coupling. In *Proceedings of the 2012 ACM Conference on Ubiquitous Computing*, 431–440, 2012.
- [7] Chao Hu, Shuang Song, Xiaojing Wang, Max Q-H Meng, and Baopu Li. A Novel Positioning and Orientation System Based on Three-axis Magnetic Coils. *IEEE Transactions on Magnetics*, 48(7):2211–2219, 2012.
- [8] Chihiro Takeshima, Katsuhiko Kaji, Kei Hiroi, Nobuo Kawaguchi, Takeshi Kamiyama, Ken Ohta, and Hiroshi Inamura. A Pedestrian Passage Detection Method by using Spinning Magnets on Corridors. In Proceedings of Adjunct Proceedings of the 2015 ACM International Joint Conference on Pervasive and Ubiquitous Computing and Proceedings of the 2015 ACM International Symposium on Wearable Computers, 411– 414, 2015.
- [9] Kosuke Watanabe, Kei Hiroi, Satoshi Kamiyama, Hiroyuki Sano, Masakatsu Tsukamoto, Masaji Katagiri, Daizo Ikeda, Katsuhiko Kaji, and Nobuo Kawaguchi. A Three-Dimensional Smartphone Positioning Method using a Spinning Magnet Marker. In Proceedings of 2017 Tenth International Conference on Mobile Computing and Ubiquitous Network (ICMU), 1–7, 2017.