How feasible is the use of magnetic field alone for indoor positioning?

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***Abstract*—The use of magnetic field variations for positioning and navigation has been suggested by several researchers. In most of the applications, the magnetic field is used to determine the azimuth or heading. However, for indoor applications, accurate heading determination is difficult due to the presence of magnetic field anomalies. Here location fingerprinting methodology can take advantage of these anomalies. In fact, the more significant the local anomalies, the more unique the magnetic "fingerprint". In general, the more elements in each fingerprint, the better for positioning. Unfortunately, magnetic field intensity data only consists of three components. Since true north (or magnetic north) is generally unknown, even with help of the accelerometer to detect the direction of the gravity, only two components can be extracted, i.e. the horizontal intensity and the vertical intensity (or total intensity and inclination). Furthermore, moving objects containing ferromagnetic materials and electronic devices may affect the magnetic field. Tests were carried out to investigate the feasibility of using magnetic field alone for indoor positioning. Possible solutions are discussed.**

Keywords-Fingerprinting; Magnetic field

I. INTRODUCTION

The last three decades have seen a revolutionary in the development of Global Navigation Satellite Systems (GNSSs). Positioning and navigation in outdoor environments is no longer a problem. However, a GNSS fails to operate where it is not possible to receive enough good quality satellite signals, such as inside most buildings and in "urban canyon" environments. Alternative technologies are sought for such difficult environments.

Indoor positioning technologies can be classified into three categories: technologies based on signals-of-opportunity, technologies based on pre-deployed infrastructure, and others. The signals-of-opportunity are signals (radio frequency – RF - signals are the most common) that are not intended for positioning and navigation, such as signals of WiFi, television and AM radio. Since these signals are designed for other purposes, and given the reality of the harsh signal propagation environment, using them for positioning to achieve high accuracy is a very difficult, if not impossible, task [1, 2]. A methodology known as "fingerprinting" is widely used where signal propagation is unpredictable or where direct line-of-sight propagation is not typical (including presence of multipath). The low cost and wide coverage of such methods are the main advantages. There are many positioning technologies that require the deployment of infrastructure, such as positioning systems using infrared, ultrasound and ultra wide band [3-5], as well as bespoke RF-based systems. Deploying new infrastructure is costly, and hence the coverage is often very limited – typically using "hot spot" mode. However, if a reliable and accurate positioning result is required, such technologies typically have to be used. Other positioning technologies include inertial navigation systems, vision-based systems, etc. [6, 7].

Using a magnetic field for positioning could be categorised in either of the first two categories depending on the ways in which the magnetic field is used. If artificially generated magnetic fields are used, pre-deployed coils are required. The received strength of the magnetic field (B) can be converted to a measurement of range or distance. If the coordinates of the coils are known, trilateration can be applied to estimate the receiver's position [8]. A significant advantage of this type of system is that the artificially generated magnetic field is not affected by most obstacles, hence multipath or non-line-of-sight errors are avoided. In most of applications, the geomagnetic field is used to determine the orientation of a device [9]. However, significant magnetic disturbances in indoor environments impact on the positioning accuracy. Mitigating such perturbations is not an easy task [10]. On the other hand, the anomalies caused by magnetic disturbances could be used as a "fingerprint" to describe the environment - the more variable the local anomalies, the more unique the fingerprint. Hence the fingerprinting methodology can possibly be applied for positioning. In such a case, this approach can be considered as a technology based on signals-of-opportunity.

Using the geomagnetic field for outdoor navigation is not new. Goldenberg [11] reviewed the terrain navigation research efforts (using land topography and geomagnetic maps) in past decades. Wilson et al. [12] developed a magnetically-aided dead reckoning system to provide navigation for aircraft. In 2000, Suksakulchai [13] realised that the magnetic field disturbances could be used for indoor localisation. The researchers collected and stored the magnetically-derived heading information as a robot travelled along a hallway. Next time, the robot measured the magnetic field features and matched them with the pre-stored data. If a match was found, the robot could determine its location. Similarly, [14] investigated a leader-follower scenario whereby a lead vehicle measures the magnetic field and sends the collected information to the follower vehicle, which uses it to follow the same path as the lead vehicle. A small area map-matching scenario was also investigated, and decimeter-level positioning accuracy was achieved. In [15] a magnetic sensors array was used to detect the indoor magnetic field intensity, and several metres accuracy was claimed. Using Magnetic field for Simultaneous Localization and Mapping (SLAM) was also investigated [16].

An obvious advantage of using the magnetic field for positioning is that no infrastructure needs to be pre-deployed, which makes such a system cost effective. In general, in each fingerprint, the more elements, the better for positioning. Unfortunately, the magnetic field intensity data only consists of three components - intensities in X, Y and Z directions. Since true north (or magnetic north) is unknown, even with aid of an accelerometer to detect the direction of the gravity, only two components can be extracted, i.e. the horizontal intensity and the vertical intensity (or total intensity and inclination). Furthermore, moving objects containing ferromagnetic materials and electronic devices may affect the magnetic field. In this paper, the feasibility of using the magnetic field alone for indoor positioning was investigated. Possible solutions are discussed.

II. EARTH'S MAGNETIC FIELD

The term "magnetic field" can refer to a magnetic B field or a magnetic H field. These two fields are distinct but closely related. In vacuum

$$B = \mu_0 H \tag{1}$$

where μ_0 is the magnetic constant ($4\pi\times10^{-7}$ Vs/Am). When there is magnetic material, the relationship of these two magnetic fields can be expressed as

$$B = \mu_0(H + M) \tag{2}$$

where M is the magnetisation field, or

$$B = \mu_0\mu_r H \tag{3}$$

where μ_r is the relative permeability.

Magnetic B field is more commonly used [17] as it reveals the real cause of the magnetic field is the moving electric charge. The units of B is Tesla (T) or Gauss (G) (1T=10000G).

Many animals use the geomagnetic field naturally to navigate their way around the Earth [18]. In ancient times, Chinese and Greek scholars observed the attractive power of a magnet, and the Chinese are credited with having invented the first magnetic compass. The magnetic declination was discovered over a thousand years ago. However, the representation of the geomagnetic field in mathematical form was first made by Gauss about 200 years ago [19].

The geomagnetic field acts as a dipole magnet located at the centre of the Earth. The axis of the dipole is tilted at an angle of approximately 11 degrees with respect to the axis of the Earth's rotation. According to the widely accepted "geomagnetic dynamo" model, differences in temperature, pressure and composition within the fluid outer core (convection) and the spin of the Earth (swirling whirlpools) cause currents which in turn produce magnetic fields [20]. The Earth's magnetic field is characterised by direction and intensity. The geomagnetic field intensity ranges between approximately 23,000 and 66,000 nT [21]. The direction of the geomagnetic field is always towards magnetic north. The horizontal components of the geomagnetic field are used to determine the compass direction.

The Earth's magnetic field is described by seven non-independent parameters: declination (D), inclination (I), horizontal intensity (H), vertical Intensity (Z), the north (X) and east (Y) components of the H and total intensity (F) (refer to Fig. 1). A compass can be used to find magnetic north, which is different from so-called "true north". The true north (geographic north) is at the Earth's rotational axis and referenced by the meridian lines, while the magnetic north refers to the geomagnetic pole position. Declination is used to describe the difference between these two north directions. The value of declination varies depending on the location of magnetic north on the surface of the Earth. Inclination is the angle between the horizontal plane and the total field vector, measured positive into Earth. A common representation of the Earth's magnetic field is in X, Y and Z coordinates (refer to Fig. 1). It can also be represented by F, D and I.

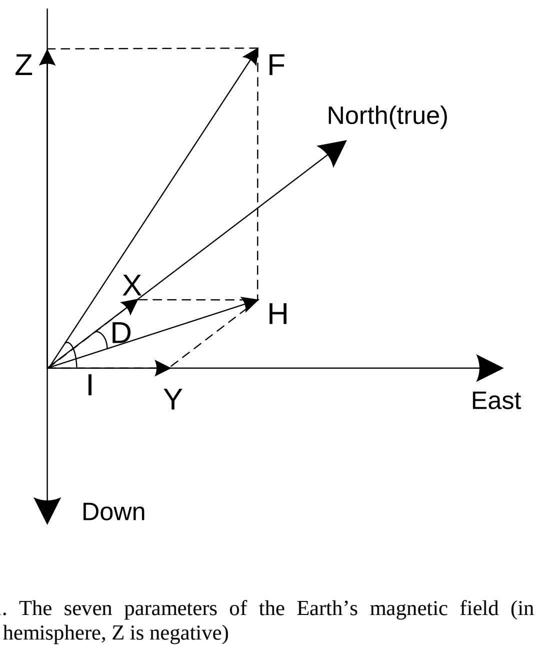

Figure 1. The seven parameters of the Earth's magnetic field (in the southern hemisphere, Z is negative)

III. INDOOR GEOMAGNETIC FIELD STABILITY

Inside buildings, significant variations of the geomagnetic field can be observed. The major cause of these variations is the steel shells of most modern buildings. Pipes, wires and electric equipment, etc., also contribute to the variations. To use geomagnetic field indoors for positioning, the measured magnetic field intensity should be stable over a relatively long period. Hence the first investigation is into indoor geomagnetic field stability. For this investigation an Xsens MTi device was used (Fig. 2). The MTi can provide 3D acceleration, 3D rate-of-turn and 3D geomagnetic field measurements. The magnetic field output is normalised to Earth field strength, hence it is in arbitrary units. The output rate can be up to 120Hz [22]. 25Hz was selected for this investigation.

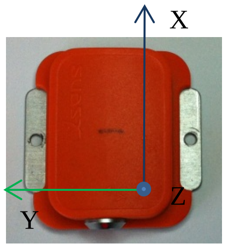

Figure 2. Xsens MTi, a gyro enhanced Attitude and Heading Reference System

To test geomagnetic field stability, three test environments were chosen: a typical office, a private garage and a computer lab. The sensor was put on a flat surface (as level as possible) and the X axis pointed to true north. Google Earth was used to find the true north. A true north calculated based on the indoor surveying points shows the Google Earth result is very close to the calculated one (within 0.5 degree). Twenty four hours of data were logged at each test point. Fig. 3 shows data logged at two test environments – office and garage. Note that the magnetic field is very stable for 24 hours. Table I lists pertinent statistics which show that the variation of the geomagnetic field is very small in any directions. The geomagnetic field variations in the computer lab are slightly larger. Further investigation revealed that there were large bodies of moving metal causing the disturbances – a lift was located approximately 3 metres away from the test point in the computer lab.

To investigate the long term stability of the geomagnetic field, the static tests were repeated about three months later. All of the intensity values were smaller than those of the previous tests. However, the inclination values were very similar. Since the sensor has been used by other researchers (including overseas), a reasonable explanation is that the configuration of the sensor (the value to normalise the intensities) has changed. Unfortunately, the configuration can't be read out. Other sensors will be used for further investigations into this effect.

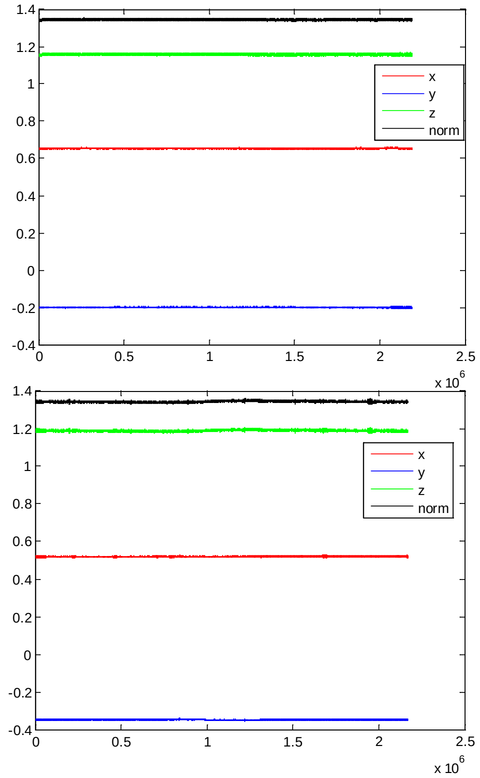

Figure 3. 24 hours static test results (top: office, bottom: garage)

TABLE I. SUMMARY OF 24 HOURS STATIC TEST RESULTS

	Mean/Std of intensity (x y z)			**Total intensity**
Office	0.654/ *0.001*	-0.200/ *0.001*	1.158/ *0.003*	*1.345*
Computer lab*	-0.156/ 0.004	-0.339/ 0.002	1.872/ 0.007	1.909
Garage	0.519/ 0.001	-0.348/ 0.001	1.189/ 0.003	1.344

*this test point is about 3m away from the lift

IV. UNIQUENESS OF THE GEOMAGNETIC FIELD

The intensity of the Earth's magnetic field is not the same at different locations. Furthermore, structural steel building elements have an impact on, and ferromagnetic contents and electronic devices as found in, indoor environments, which disturb the magnetic field significantly. However, the geomagnetic field may not be unique. To investigate this, data were collected in different environments, including several office buildings (EE, OMB, LAW), a library (LIB), a private garage (GAR), and a car park (BAR).

A. Static Tests

Firstly the static data were collected at one specific location in each environment for three minutes. Fig. 4 shows the results. The X, Y, Z components of magnetic intensities and the total magnitude are all different at the different environments. The magnetic fields can be easily distinguished by visual inspection. The magnetic field intensity distances were also calculated. The intensity distance is defined as

$$L_q = (\sum_{i=1}^{3} |m_i - M_i|^q)^{\frac{1}{q}} \quad (4)$$

where m and M are the measured magnetic intensity (a vector of 3 elements – X, Y and Z) at different locations. Manhattan distance and Euclidean distance are L_1 and L_2 respectively. Table II lists the Manhattan/Euclidian intensity distances between all six test locations. There are several things of interest. Overall, the Manhattan intensity distances are consistently larger than the Euclidian ones as the magnetic intensities used are normalised values. The intensity distances are much larger than the variances of the intensity (refer to Table I). Different test environments can be distinguished by comparing the intensity distances. However the real distances cannot be scaled by the intensity distances. For instance, the garage is about 10km away from all the other test locations, however the intensity distances are in general the shortest. This also implies that using the geomagnetic field for positioning may have difficulties.

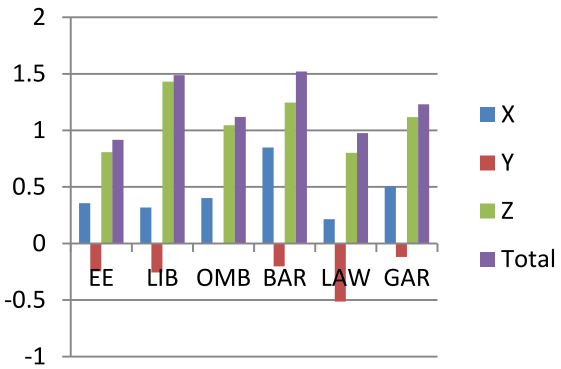

Figure 4. Comparison of the geomagnetic field intensities collected at different environments

TABLE II. INTENSITY DISTANCES (MANHATTAN/EUCLIDIAN)

Man / Euc	EE	LIB	OMB	BAR	LAW	GAR
EE		0.669	0.533	0.976	0.412	0.587
LIB	0.624		0.728	0.769	0.988	0.637
OMB	0.348	0.472		0.854	0.945	0.298
BAR	0.661	0.564	0.532		1.388	0.557
LAW	0.301	0.687	0.600	0.834		0.999
GAR	0.367	0.389	0.175	0.377	0.582	

B. Dynamic Tests

A dynamic test was then carried out to collect data at five corridors one above the other in a multi-floor building. The setup of the test is shown in Fig. 5. The height of the trolley was about 1.05m, which is approximately the height of a person holding a mobile device. The trolley was moved from the start point to the end point with a speed that was as constant as possible. Fig. 6 presents the results; clearly the magnetic fields are different at different levels in the same building. However, it cannot be seen whether the magnetic field is unique at a specific location. Although the uniqueness property may not be true, at least not many locations have the similar magnetic field pattern.

Figure 5. Equipment setup of the dynamic test

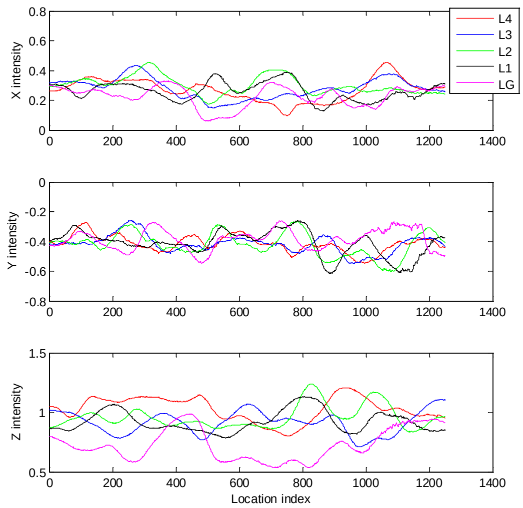

Figure 6. Comparison of the measured magnetic intensities at overlapping corridors

The same tests were repeated three months later. Fig. 7 compares the total intensities and the inclinations (the positive values are used) collected from the fourth floor of the building. There is an offset in intensity values between the two sets of data. However the inclination values are consistent despite the speed of the trolley not being constant and the test line not being exactly followed as in the previous test (human error is inevitable). The cross-correlation coefficient is greater than 0.99/0.97 (total intensity/inclination) which means the two sets of data are very similar.

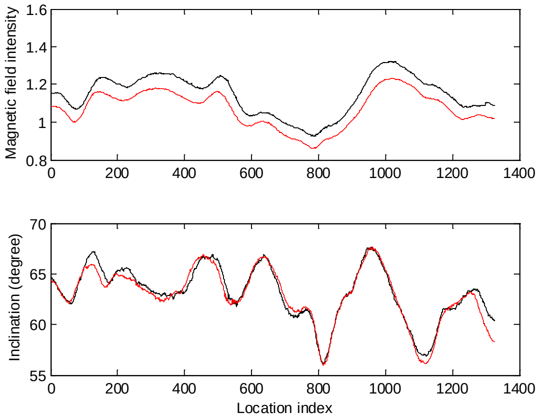

Figure 7. The data collected at different dates (with 3 month gap) in the same corridor

C. Small Area Tests

To investigate the changes of the geomagnetic field across a small area, two grids - a large one (8 by 8) and a small one (6 by 6) - were selected. The spacing of the large grid was 30.5cm while that of the small one was 5cm. In fact, the small grid is part of the large grid (refer to Fig. 8). Data were collected at each intersection for 30s. In total there were 64 data sets for the large grid and 36 data sets for the small grid. The average intensities in the X, Y and Z directions are shown in Fig. 9. The changes of the geomagnetic field in an area of 4.6m^2 are significant - the magnetic field intensity varies between 0.315 and 0.411, -0.267 and -0.012, 0.808 and 1.108, in the X, Y and Z directions respectively. Even in an area of 0.09m^2, the changes were noticeable. The intensity varies between 0.319 and 0.338, -0.130 and -0.116, 0.994 and 1.005, in the X, Y and Z directions respectively. This suggests that the geomagnetic field could be used for precise positioning.

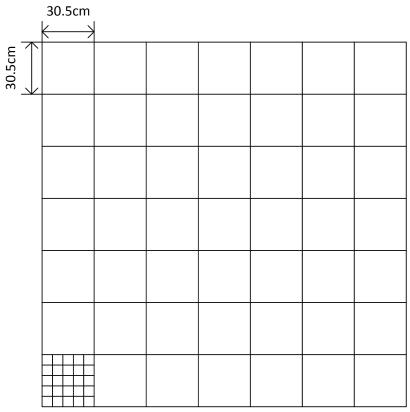

Figure 8. A large grid and a small grid for testing

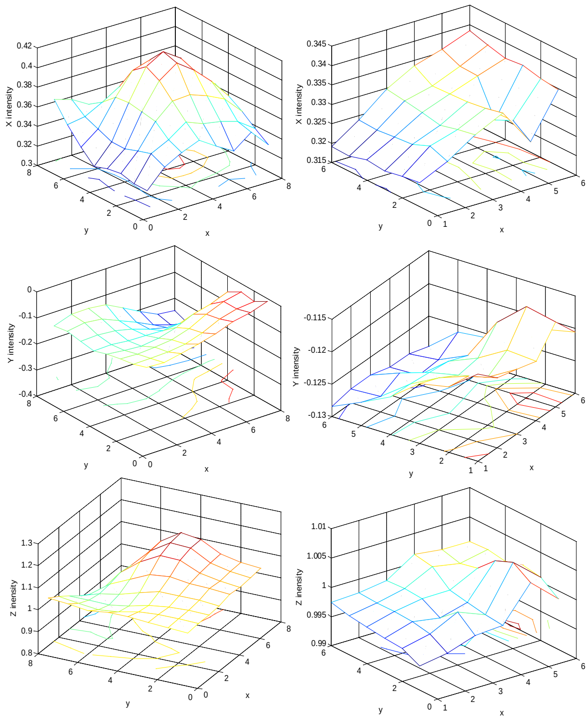

Figure 9. The average intensities in the X, Y and Z directions collected in the grid tests

D. Vertical Test

Finally, the change of the magnetic field in the vertical direction was studied. A bipod was set up as shown in Fig. 10 (left). The sensor's location was changed from 0 to 1m height with the step size of 5cm, so that in total there were 20 test points. Fig. 10 (right) shows the changes in the values of the intensities. The differences are not as significant as for the horizontal test.

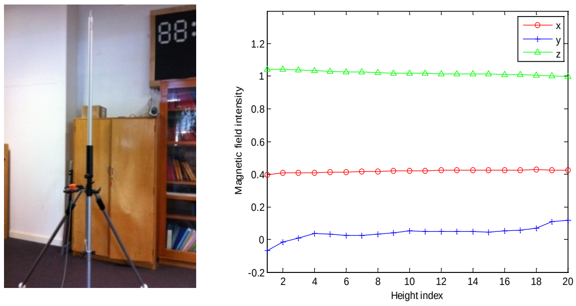

Figure 10. Vertical test setup (left) and results (right)

V. INTERFERENCE

In an indoor environment, moving objects containing ferromagnetic materials and electronic devices may affect the magnetic field. If the impact is significant, using variations of the geomagnetic field for positioning would be difficult. To investigate potential interferers, several objects are selected. Typically the lift is the largest moving metal object in a building. The sensor was first placed about 30cm away from a lift (there are two lifts installed in the test building side-by-side, hence it is the impact of two lifts that is sensed), then the distance was gradually increased to about 9m. Data were collected at all test locations. The two lifts were operating during the test. The variation of the intensities measured at each test location are plotted in Fig. 11. The variation decreases very rapidly with the distance from the lifts, and at about a distance of 7 to 8m the influence of the lifts is negligible. This is consistent with the theoretical magnetic field propagation models. Obviously, using the magnetic field for positioning close to lifts would have difficulties. However, if significant variation of the intensity can be detected, the sensor could be assumed to be close to a large moving metal object – very likely a lift.

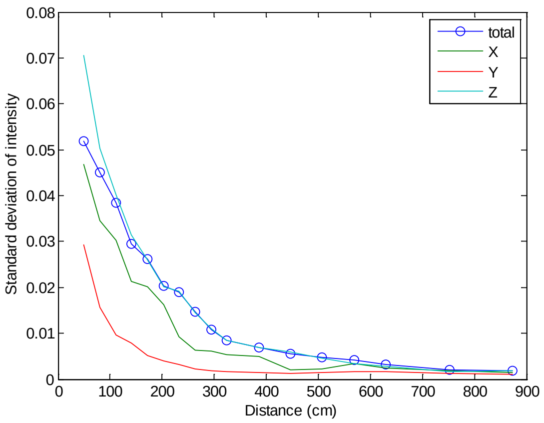

Figure 11. The influence of lifts on the magnetic field

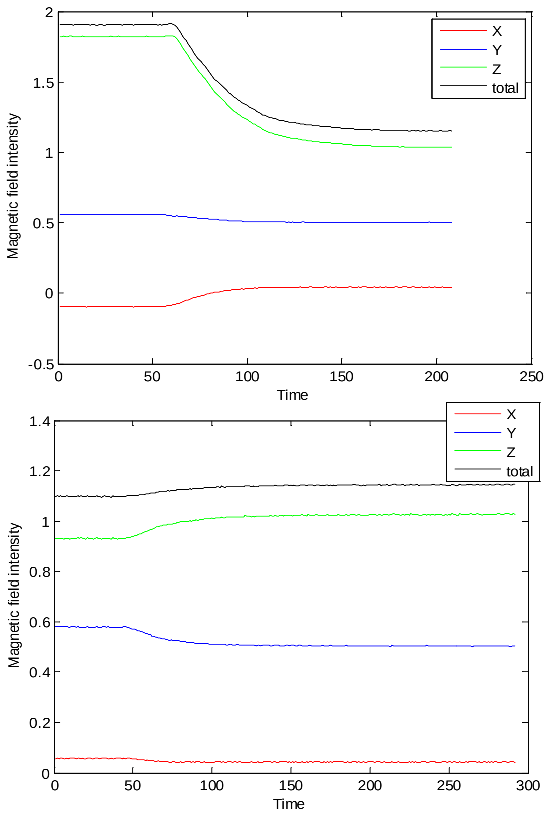

Figure 12. The influence on the magnetic field intensity of mobile phones (top: N95, bottom: iPhone 4)

Other small objects such as a mobile phone, metal tin, and headphones were also tested. In these tests the sensor was fixed and the small objects were placed very close to the sensor and then moved away slowly with constant speed. Fig. 12 plots the magnetic field intensities detected by the sensor when two mobile phones were tested. It shows the impact of the phones on the magnetic fields. The influence is significant (especially for the N95) if the object is very close to the sensor. However, as the distance between the phone and the sensor increases, the influence reduces quickly. When the distance is more than 15cm the influence from both phones can be neglected. In the case of a headphone, a metal tin, a laptop, and a metal cabinet, the separation distance beyond which the object's influence is negligible varies (8cm, 26cm, 32cm and 1.5m respectively). The size of the object is an obvious factor – the larger the object the greater the separation distance. For instance, the metal cabinet was much bigger than all other objects tested and the separation distance was the longest.

VI. USING MAGNETIC DENSITY AS FINGERPRINT FOR POSITIONING

The results of the tests show that the indoor geomagnetic field is stable, and that its characteristics change with location. Therefore applying the fingerprinting methodology for positioning is possible. An obvious drawback of using geomagnetic field information is that the number of elements that can be used to create the fingerprint is small - intensities in X, Y and Z directions only. To use these in many applications other than SLAM [16], however, true north (or magnetic north) should be known, or the manner of measuring the magnetic field, e.g. the attitude of the sensor, in the two phases of fingerprinting, i.e. training phase and positioning phase [2], should be the same. Neither of these two requirements can be easily meet in many applications. For instance, the way a user holds a mobile device can be completely different, hence the relationship between the sensor-fixed coordinate system and the earth-fixed reference coordinate system is different. There is a possible way to address this problem if an accelerometer can be used to sense the direction of gravity, however the number of elements for each fingerprint will decrease to two. Fig. 13 illustrates how this works. The relationship between the sensor-fixed coordinate system and the earth-fixed coordinate system and true north (*X'*) are unknown. It is impossible to calculate the *X'* and *Y'* components of *b*. On the other hand, the *Z'* component can be calculated and the component in the *X'Y'* plane is the same no matter the direction of true north (*X'* should point to true north, but this direction is unknown). The magnitude of vector *b* can be easily obtained and θ can be calculated using the following formula:

$$cos\left(\frac{\pi}{2}-\theta\right)=\frac{a_x b_x+a_y b_y+a_z b_z}{\sqrt{a_x^2+a_y^2+a_z^2}\sqrt{b_x^2+b_y^2+b_z^2}} \qquad (5)$$

Using three elements (intensities in X, Y and Z directions) and two elements (intensities in the Z direction and XY plane) for fingerprint-based positioning are discussed below.

To apply a fingerprinting methodology, a database must be created in a so-called "training" phase. The data collected during the tests described in the previous sections were used for training purposes. The small grid test was first investigated (refer to Figs 8 and 9, and the context). Two databases were created, using the three element approach and the two element approach. Then one of the reference points was removed from the database and was used as a test point. The basic nearest neighbour (NN) algorithm (using Manhattan distance or Euclidian distance) was used to estimate the test point's position. A similar test was carried out using the large grid test data. After that, the small grid intersections were used as test points and the large grid intersections were used as reference points (large/small grid test). Table III lists the resultant positioning errors. It is clear that using the three element approach is better than using the two element approach, and that there is not much difference using different intensity distance (Manhattan or Euclidian). In the cross-validation test, the average error of the former is about 2/3 of that of latter, and the maximum error of the former is much smaller than that of the latter. In the large/small grid normal test, the performance of the former (using 3 elements) is even better. There are several large positioning errors in each test which contribute significantly to the magnitude of the average errors. Typically the cross-validation test performs worse than the normal test because the nearest reference point was removed from the database, which means the minimum positioning error is the spacing of the grid. In general the accuracy is good even when only two elements are used and one of the factors influencing the accuracy is the density of reference points. However, creating a database with dense reference points is not an easy task.

Since using either Manhattan or Euclidian distance did not make much difference, only Manhattan distance has been considered in the remainder of the tests.

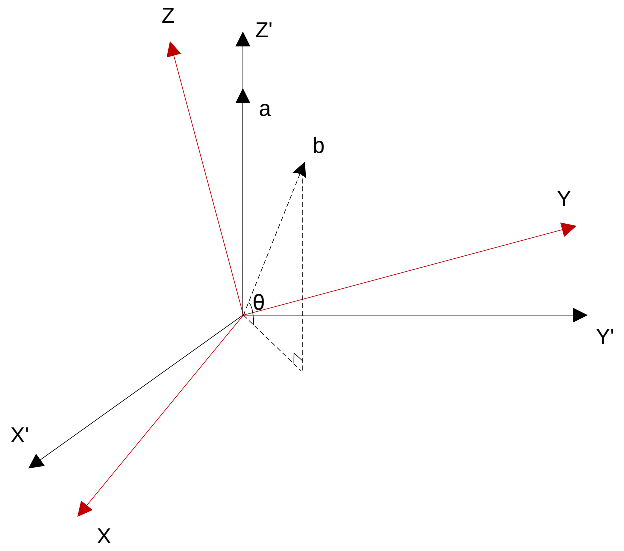

Figure 13. Using gravity to derive the vertical and horizontal components of the magnetic field intensity (Red: sensor-fixed coordinate system, black: earth-fixed coordinate system, *a* is the opposite direction of gravity; *b* is the magnetic intensity measurement)

TABLE III. POSITIONING ERROR USING 3 ELEMENT AND 2 ELEMENT DATABASES FOR GRIDS TESTS

		3 element			2 element		
		Mean(cm)	Min(cm)	Max(cm)	Mean(cm)	Min(cm)	Max(cm)
Small grid	Man	5.8	5.0	10.0	8.7	5.0	20.6
	Euc	5.9	5.0	10.0	8.5	5.0	20.6
Large grid	Man	41.3	30.5	155.5	63.9	30.5	195.3
	Euc	40.3	30.5	155.5	65.5	30.5	195.3
Large/Small grid	Man	18.3	0	64.2	45.8	5.5	154.5
	Euc	18.8	0	43.7	46.1	5.5	154.5

The multi-corridor test was the second one to be investigated. The method utilised to collect the data is more efficient though less accurate as a human cannot move with a constant speed. A database was created using all data collected in five overlapping corridors. Similar to previous cross-validation tests, the data collected for database creation also was used as test data. The true coordinates of the reference points and test points were calculated based on the positions of the start point, end point and the time stamp of the measurements. Table IV summarises the positioning results of the test points in different levels assuming the right level was unknown. Most of the time the correct level can be determined. However the possibility to locate the test point at the right level decreases significantly when the two element approach was used. It is also possible to locate the test point on a very wrong level, i.e. not the adjacent level. This is one of the big challenges in using the geomagnetic field alone for positioning. Assuming the correct level was known (using other constraints or other positioning technology), Table 5 lists the positioning errors. The average error is quite small, especially when the three element approach was used. There are few very large errors, which can be over 20m, however the majority of the errors are below 1m. The last column of Table V gives the percentage of solutions where better than 1m accuracy was achieved.

TABLE IV. THE RESULTS OF POSITIONING THE TEST POINTS IN DIFFERENT LEVELS (IN PERCENTAGES) IF 5 LEVELS ARE CONSIDERED (THE CORRECT LEVEL WAS UNKNOWN)

	Level	4	3	2	1	G
3 elements	4	*98.8*	0.6	0	0.5	0.1
	3	0.5	*98.3*	0.4	0.4	0.5
	2	0.2	0.5	*98.2*	1.1	0
	1	0.8	0.3	0.7	*98.3*	0
	G	0.1	0.3	0.1	0	*99.5*
2 elements	4	*81.9*	5.0	4.2	8.1	0.7
	3	6.0	*74.3*	8.9	8.2	2.6
	2	5.9	9.0	*75.1*	7.0	3.0
	1	9.0	8.4	7.0	*72.3*	3.2
	G	1.0	2.3	3.2	3.4	*90.1*

TABLE V. POSITIONING ERRORS (IN METRES) IF THE LEVEL IS KNOWN

	Level	mean	min	max	within 1m (%)
3 elements	4	0.10	0.03	33.94	99.3
	3	0.04	0.03	0.36	100
	2	0.13	0.03	18.33	99.1
	1	0.04	0.03	0.65	100
	G	0.09	0.03	21.20	99.5
2 elements	4	1.05	0.03	34.00	90.4
	3	1.39	0.03	28.73	88.4
	2	1.03	0.03	28.91	90.8
	1	1.21	0.03	26.80	90.6
	G	1.02	0.03	25.60	92.3

Similar tests have been carried out for different buildings. If the correct building was unknown, using the geomagnetic field fingerprint alone could position the test point in the wrong building. Other information should therefore be utilised to constrain the area where the test point is located, or some other positioning technology, such as WiFi, can be in combination.

VII. CONCLUDING REMARKS

The use of magnetic field disturbances for indoor positioning has obvious advantages: no pre-deployed infrastructure is required, the magnetic field is everywhere and relatively stable. However, there are also significant challenges. Firstly the number of elements that can be used to create the fingerprint database is small, maximum three, though the number could fall to two in many applications. This makes the fingerprinting methodology not very reliable - sometimes the user could be located in a wrong building! It is possible to use several magnetic sensors together to increase the number of elements, however this increases the complexity of the mobile device and requires a better training survey of the area of interest. Secondly the change of magnetic field with location is quite significant. This is good for precise positioning – better than metre-level, even decimetre-level of accuracy is possible. On the other hand, it makes the surveying of the area of interest more difficult. Methods are needed to create the database in an efficient manner. Lastly, magnetic interferences should be considered, especially in areas close to lifts.

Several tests have been reported in this paper, however more are needed. For instance, the height of the sensor in the training phase and positioning phase could be completely different, how significantly will this influence the positioning results? Many of the tests have been conducted using cross-validation tests, but to reflect real world situations test data collected separately are necessary. Furthermore it is impossible to survey everywhere with a high density of reference points, and interpolation must be applied. In addition, different sensors behave differently, and these differences should be investigated. Combining geomagnetic field positioning with other technologies is also an interesting topic, for instance using WiFi fingerprinting with extra magnetic fingerprints may improve the positioning accuracy.

There is a fundamental problem of fingerprint-based positioning, e.g. the relationship of the real distance and the vector distance (in this case it is intensity distance) especially for short distances. This relationship impacts on the estimating errors in fingerprint-based positioning systems [23][24]. Further investigation is required.

REFERENCES:

[1] B. Li, A. G. Dempster, J. Barnes, C. Rizos and D. Li, "Probabilistic algorithm to support the fingerprinting method for CDMA location," in Proc. Int. Symp. on GPS/GNSS 2005, 2005, .

[2] B. Li, Y. Wang, H. K. Lee, A. Dempster and C. Rizos, "Method for yielding a database of location fingerprints in WLAN," IEE Proceedings-Communications, vol. 152, pp. 580-586, 2005.

[3] S. Gezici, Z. Tian, G. Giannakis, H. Kobayashi, A. Molisch, H. Poor and Z. Sahinoglu, "Localization via ultra-wideband radios: a look at positioning aspects for future sensor networks," Signal Processing Magazine, IEEE, vol. 22, pp. 70-84, 2005.

[4] N. B. Priyantha, A. Chakraborty and H. Balakrishnan, "The cricket location-support system," in Proceedings of the 6th Annual International Conference on Mobile Computing and Networking, Boston, Massachusetts, US, 2000, pp. 32-43.

[5] R. Want, A. Hopper, V. Falcão and J. Gibbons, "The active badge location system," ACM Transactions on Information Systems, vol. 10, pp. 91-102, 1992.

[6] J. Collin, O. Mezentsev and G. Lachapelle, "Indoor positioning system using accelerometry and high accuracy heading sensors," in 16th Int. Tech. Meeting of the Satellite Division of the U.S. Institute of Navigation, Portland, US, 2003, .

[7] V. Paelke and C. Reimann, "Vision-based interaction-a first glance at playing MR games in the real-world around us," in PerGames 2005, Munich, Germany, 2005, pp. 92-97.

[8] J. Blankenbach and A. Norrdine, "Position estimation using artificial generated magnetic fields," in Indoor Positioning and Indoor Navigation (IPIN), 2010 International Conference on, 2010, pp. 1-5.

[9] V. Y. Skvortzov, H. K. Lee, S. W. Bang and Y. B. Lee, "Application of electronic compass for mobile robot in an indoor environment," in Robotics and Automation, 2007 IEEE International Conference on, 2007, pp. 2963-2970.

[10] M. H. Afzal, V. Renaudin and G. Lachapelle, "Multi-Magnetometer Based Perturbation Mitigation for Indoor Orientation Estimation," NAVIGATION, vol. 58, 2011.

[11] F. Goldenberg, "Geomagnetic navigation beyond the magnetic compass," in Proceedings of IEEE/ION PLANS 2006, San Diego, CA, USA, 2006, pp. 684-694.

[12] J. M. Wilson, R. J. Kline-Schoder, M. A. Kenton, P. H. Sorensen and O. H. Clavier, "Passive navigation using local magnetic field variations," in Proceedings of the 2006 National Technical Meeting of the Institute of Navigation, Monterey, CA, USA, 2006, pp. 770-779.

[13] S. Suksakulchai, S. Thongchai, D. Wilkes and K. Kawamura, "Mobile robot localization using an electronic compass for corridor environment," in Systems, Man, and Cybernetics, 2000 IEEE International Conference on, 2000, pp. 3354-3359 vol. 5.

[14] W. Storms, J. Shockley and J. Raquet, "Magnetic field navigation in an indoor environment," in Ubiquitous Positioning Indoor Navigation and Location Based Service (UPINLBS), 2010, pp. 1-10.

[15] J. Chung, M. Donahoe, C. Schmandt, I. J. Kim, P. Razavai and M. Wiseman, "Indoor location sensing using geo-magnetism," in Proceedings of the 9th International Conference on Mobile Systems, Applications, and Services, 2011, pp. 141-154.

[16] I. Vallivaara, J. Haverinen, A. Kemppainen, J. Roning, "Magnetic field-based SLAM method for solving the localization problem in mobile robot floor-cleaning task," Advanced Robotics (ICAR), 2011 15th International Conference on , 2011, pp.198-203.

[17] R. A. Serway, J. S. Faughn and C. Vuille, College Physics. Brooks/Cole Pub Co, 2011.

[18] J. L. Gould, "Magnetic field sensitivity in animals," Annu. Rev. Physiol., vol. 46, pp. 585-598, 1984.

[19] R. T. Merrill, M. W. McElhinny, P. L. McFadden and ScienceDirect (Online service), "The magnetic field of the Earth: Paleomagnetism, the core, and the deep mantle," 1996.

[20] J. A. Jacobs, The Earth's Core. Academic Pr, 1987.

[21] S. Maus, S. Macmillan, S. McLean, B. Hamilton, A. Thomson, M. Nair and C. Rollins, "The US/UK World Magnetic Model for 2010-2015," 2010.

[22] Xsens Technologies, "MTi and MTx user manual and technical documentation," 2010.

[23] A. G. Dempster, B. Li and I. Quader, "Short baseline propagation characteristics of deterministic wireless fingerprinting systems for localisation," in 6th IEEE Consumer Communications and Networking Conference, 2009. CCNC 2009, Las Vegas, Nevada, 2009, pp. 1-5.

[24] A. G. Dempster, B. Li and I. Quader, "Errors in determinstic wireless fingerprinting systems for localisation," in Wireless Pervasive Computing, 3rd International Symposium on, Santorini, Greece, 2008, pp. 111-115.