Multi-Magnetometer Based Perturbation Mitigation for Indoor Orientation Estimation

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ABSTRACT: Determining orientation with respect to a known reference plays an important role in almost all modes of navigation. As the sensors required for measuring magnetic field have found their way into portable navigation devices, researchers have started investigating their application to orientation estimation in different environments. Nevertheless, the success of these sensors for orientation estimation is conditioned by their capacity to sense Earth’s magnetic field in environments full of magnetic anomalies like urban canyons and indoors. These artificial fields contaminate Earth’s magnetic field measurements, making orientation estimation very difficult in heavily perturbed areas. To overcome the effect of magnetic anomalies, a perturbation mitigation technique is proposed that utilizes multiple magnetometers. This mitigation technique is then used for estimating Earth’s magnetic field indoors thus providing users with better magnetic orientation estimates. Performance of the proposed mitigation technique is assessed for pedestrian navigation in a shopping mall.

INTRODUCTION

The process of providing pedestrians with their location and guidance information, which in some way can be used for simplifying the task of reaching a destination, is called pedestrian navigation. It somewhat differs from other navigation applications (e.g., land vehicle, sea vessel, and aircraft navigation) due to the diversity of environments in which the pedestrian navigation system has to work. Sometimes the pedestrian is strolling in a park outdoors while other times the subject is in an urban environment shopping or going to work. The rest of the time is spent indoors. All of these environmental changes constitute different navigation scenarios for pedestrian navigation. Among all of the possible scenarios for pedestrian navigation, the indoor navigation scenario is the most challenging. These challenges arise from the availability and reliability of information for estimating the navigation parameters. The challenges and differences that can be directly identified come from the nature of sensors and usable navigation technologies. For example, Global Navigation Satellite Systems (GNSS) cannot be considered as a reliable navigation technology indoors [1]. Also the diversity of environments for pedestrian navigation demands an autonomous system that can provide users with navigation parameters irrespective of the availability of certain man-made information sources. For this purpose, the use of planetary/universal physical forces for estimating navigation parameters is considered. Systems incorporating sensors that can measure these forces fall under the category of aided navigation systems. These systems incorporate a very popular and well developed navigation technology known as the inertial navigation system (INS) along with some extra information sources, e.g., barometers and magnetometers. The INS solution can be very accurate and reliable depending on the quality of the integrated sensors. In the context of pedestrian navigation, however, cost, size, and power consumption dictate the sensor selection rendering these systems to lower accuracy and reliability [2]. In order to improve the navigation solution of low cost INS, other navigation aids are utilized. While estimating the attitude of the portable device, Earth’s magnetic field can be used to compensate for the errors associated with gyroscopes. This is very effectively achieved outdoors [3], but as one moves indoors, the presence of magnetic anomalies generated by man-made infrastructure starts affecting the sensor measurements introducing errors in the heading estimation.

In order to mitigate the effects of these magnetic anomalies/perturbations, a novel idea is presented in this paper, which improves the indoor magnetic heading estimates with the help of multiple magnetometers.

This paper first presents the results of a detailed survey conducted in different indoor environments
to assess the impact of magnetic perturbations on heading estimates. Next a detailed theoretical model of Earth’s magnetic field in the presence of magnetic perturbations is presented. Based on this model, the critical parameters for identifying the effects of perturbations are identified. An explanation of the hardware platform designed for collecting indoor magnetic field data follows. This platform is a direct outcome of the indoor magnetic field modeling. Next a perturbation detector capable of identifying, as well as quantifying the effect of perturbations on heading estimates is presented. The outcome of this perturbation detector is then used with an attitude estimation filter, which is based on the indoor magnetic field estimator explained in the preceding section. Finally the performance of the proposed algorithms for estimating magnetically derived heading in the presence of perturbations is assessed in a shopping mall. Results show a substantial improvement when multiple magnetometers are used to estimate the heading as compared with the use of a single tri-axis magnetometer.

INDOOR MAGNETIC FIELD ASSESSMENT

In order to quantify the effects of artificial magnetic perturbations on the measurement of Earth’s magnetic field, a magnetic field survey was conducted in different indoor environments. A high resolution and high sensitivity fluxgate magnetic field sensor was utilized to provide the most accurate measurement of the local field [4]. Table 1 summarizes its main specifications. To assess the impact of errors contained in Earth’s magnetic field measurements on the heading estimates, the magnetically derived heading has to be compared with a reference. True heading is computed using the SPAN-CPT HG1700 GNSS/INS from NovAtel [5]. It is composed of a tactical grade Inertial Measurement Unit (IMU) and a global positioning system (GPS) and global navigation satellite system (GLONASS) receiver. Knowledge about Earth’s magnetic field at the data collection site is necessary so as to distinguish between the fields due to local perturbations and the one induced by Earth. The last is predicted using the Canadian Geomagnetic Reference Field (CGRF) which continuously observes and models Earth’s magnetic field parameters in Canada accurate to 150 nano Tesla (nT) [6].

Hardware Setup

Figure 1 depicts the overall data collection platform composed of the magnetic field sensor (fluxgate), tactical grade IMU, GNSS receiver, and sensor data logger. Three-dimensional (3D) rotational maneuvers were performed for estimating the errors associated with the magnetic field sensors using a complete tri-axis magnetometer calibration algorithm in the magnetic domain [7]. The calibration is performed for the complete mobile hardware setup used in all experiments for collecting indoor magnetic field as well as the INS/GNSS reference data [8].

Post-Processing of the Data

The data collected using the tactical grade IMU and GNSS is post-processed using NovAtel’s Inertial Explorer software. Forward and backward smoothing is performed to get the best possible post-processed outcome. Based on a detailed study conducted for assessing the quality of the reference solution, it was found that with indoor dwell times of nine minutes, heading can be estimated with an accuracy of 1° using precise GNSS/IMU alignments at the beginning and end of each period. The indoor magnetic field based heading estimates are obtained using the fluxgate magnetometer measurements. The fluxgate sensor has been first calibrated in 3D and then the magnetic field components are transformed to the local level frame using the roll and pitch angles obtained from the INS reference system. This heading is then compensated

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Details</th>
</tr>
</thead>
<tbody>
<tr>
<td>Type</td>
<td>Fluxgate</td>
</tr>
<tr>
<td>Manufacturer</td>
<td>Bartington</td>
</tr>
<tr>
<td>Axis</td>
<td>Three</td>
</tr>
<tr>
<td>Measuring range</td>
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<tr>
<td>ADC Resolution</td>
<td>12 bits</td>
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<tr>
<td>Sensitivity</td>
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</tr>
</tbody>
</table>

Table 1—Technical Specifications of the Fluxgate Sensor
using the declination angle, which is obtained using the CGRF model.

**Selection Criteria for Indoor Environments**

The effect of perturbations on Earth’s magnetic field measurements depends on the frequency of occurrence and the magnitude of the local magnetic perturbation. Thus, the building structure type as well as its usage will govern the amount of perturbations expected in a particular indoor environment. Consequently, the magnetic field survey was conducted in a diverse set of buildings including old and new office constructions, schools, a student center, and a shopping mall. Table 2 summarizes the different types of buildings selected for this analysis.

**Effect of Perturbations on Indoor Heading Estimates**

After performing the survey of the selected buildings, magnetically derived heading was estimated and compared with the reference heading to quantify the errors due to perturbations. The differences between the estimated and the reference headings are divided into classes of 2° each. This value was defined based on the fact that the fluxgate sensor’s noise level is causing a fluctuation of ±0.8° in the heading estimates. This introduces an uncertainty band of 1.6°, which is rounded to 2° to ease the analysis. Figure 2 gives an overall picture of the heading error distribution in the different indoor environments.

These statistical results show that the buildings with similar construction and usage have similar heading error distributions. This supports the hypothesis that magnetic perturbations are strongly related to the infrastructure. Indeed the environments with fairly wide corridors, like the shopping mall, have a better error distribution than other buildings. Similarly, the distribution of the magnetic perturbation sources in different buildings can be studied providing a better insight into the effect of perturbations on heading estimates. Figure 3 depicts the overall distribution of perturbation sources.

Comparing Figure 2 and Figure 3, it can be observed that there is a discrepancy between heading errors and the magnitude of the perturbations. For example, in Figure 2, the constructions ICT and CCIT have comparable heading error distributions. However, their corresponding perturbation distributions in Figure 3 are not similar. In fact, the perturbation distribution of ICT is comparable to that of McEwan student center. The following important conclusion can be made from this observation: *It is not the magnitude of the perturbation that governs the errors in the heading estimation but rather its effect on the direction of the local magnetic field vector*. To further understand the effect of perturbations on the local magnetic field, Earth’s magnetic

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**Table 2—Indoor Environments for Magnetic Field Assessment**

<table>
<thead>
<tr>
<th>Buildings' name</th>
<th>Construction</th>
<th>Open Space</th>
<th>IT Hardware</th>
<th>Shops</th>
</tr>
</thead>
<tbody>
<tr>
<td>Calgary Center of Innovative Technology (CCIT) - UofC</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td></td>
</tr>
<tr>
<td>Information &amp; Communications Technologies (ICT) - UofC</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td></td>
</tr>
<tr>
<td>Engineering building - UofC</td>
<td>X</td>
<td></td>
<td></td>
<td>X</td>
</tr>
<tr>
<td>MacEwan student center - UofC</td>
<td>X</td>
<td>X</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Market mall - Calgary</td>
<td>X</td>
<td></td>
<td></td>
<td>X</td>
</tr>
</tbody>
</table>

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![Fig. 2–Heading error distribution for different indoor environments](image1)

![Fig. 3–Perturbation distribution in different indoor environments](image2)
field needs to be modeled in the presence of such perturbations.

**INDOOR MAGNETIC FIELD MODELING/SIMULATION**

In open field outdoor environments, Earth’s magnetic field, which is usually modeled as a dipole [9], is the only source of magnetic field that can be sensed by an orthogonal arrangement of magnetometers. Using the X and Y axis components of this field measurement, which constitute the horizontal field, the magnetically derived heading with respect to the magnetic North can be estimated as

$$\psi = \tan^{-1} \left( \frac{B_x}{B_y} \right)$$ (1)

where $B_x$ and $B_y$ are the local magnetic field vector measurements described in Figure 4.

The magnetic field of a dipole is characterized by its magnetic moment $M$. In the presence of multiple dipoles, the magnetic field is defined by the sum of all magnetic moments [9]. The combined magnetic moment is given by

$$M = \sum M_i$$ (2)

where $i$ represents the number of dipoles.

The magnetic vector potential at the observation point $p$ is governed by the density of magnetic moments at that point and is given by

$$M = \int V P(p) dV$$ (3)

where $P(p)$ is the density of moments at the observation point $p$ and the volume integral is defined by the field observation region.

Now the magnetic vector potential ($A$) of the combined magnetic moment in Equation (3) becomes

$$A(p) = \frac{\mu_0}{4\pi} \int \frac{P(p) \times R}{|R|^3} dV$$ (4)

$$B(p) = \nabla \times A(p)$$

where $\mu_0$ is the magnetic permeability of air, $R$ is the separation vector between the observation point and the origin of the cumulative dipole moment, and $\nabla$ is the gradient operator [9].

Equation (4) leads to the following relationship between the combined magnetic moment and local magnetic field.

$$B_x = \frac{3\mu_0 M rz}{4\pi(r^2 + z^2)^{5/2}} \sin \Phi$$

$$B_y = \frac{3\mu_0 M rz}{4\pi(r^2 + z^2)^{5/2}} \cos \Phi$$

$$B_z = \frac{\mu_0 M}{4\pi(r^2 + z^2)^{5/2}} (2z^2 - r^2)$$ (5)

Here, $r$ and $z$ are the components of the separation vector $R$, and $\Phi$ is the orientation angle of the sensor with respect to the Cartesian coordinates defining the magnetic moment. These parameters and the combined magnetic field in the presence of two dipoles, arbitrarily oriented with respect to each other, are depicted in Figure 5.

**Earth’s Magnetic Field in the Presence of an Artificial Dipole**

Earth’s magnetic field can be modeled/simulated in an indoor environment in the presence of mag-
netic dipoles known as magnetic perturbations. These perturbations are due to either electromagnetic devices or magnetization of man-made structures in the presence of an external magnetic field.

As the separation between the observation point and the center of Earth’s dipole is large, it can be assumed that any small displacement on Earth’s surface has no impact on the measured magnetic field. Mathematically this becomes

\[
R = \sqrt{r^2 + z^2} \approx \sqrt{r^2} \text{ as } z = r
\]  

(6)

where \(r\) is the horizontal distance between the observation point and the origin of the magnetic dipole, \(z\) is the vertical distance, and \(R\) is the magnitude of the separation vector.

Therefore, as the observation point moves indoors, the magnetic dipole (here portraying Earth’s dipole) also moves with it, thus keeping the distance between the origin of the magnetic moment and the observation point constant. Other artificial dipoles continue appearing and disappearing in the sensitivity range of the magnetometers. This is graphically depicted in Figure 6. \(M_E\) is the magnetic moment creating Earth’s magnetic field whereas \(M_P\) is that of a perturbation source.

When one moves in the direction as suggested by the arrow in Figure 6, the magnetic field generated by the perturbation source increases in magnitude as the distance \(R_2\) reduces. This causes the magnetic field components, which are supposed to remain constant (no rotation maneuver taking place), to undergo magnitude changes resulting in changing the overall orientation of the local magnetic field vector. This phenomenon is further illustrated in Figure 7, Figure 8 and Figure 9.

Figure 7 depicts the magnetic field components sensed by a sensor following a linear motion in the absence of any perturbation source. These components are those of Earth’s magnetic field. Figure 8 depicts the magnetic field of a perturbation source while the magnetometer moves towards and away from it. Finally, Figure 9 portrays the magnetic field profile of the combined magnetic moments. Here it can be observed that at the beginning and at the end, the magnetic field components are dominated by Earth’s magnetic field because the distance between the observation point and the pertur-
bation source is very large. However in the middle of this magnetic profile, the magnetic field components experience changes in magnitude causing variations in the local magnetic field due to the perturbation.

Use of Multiple Magnetometers to Study the Impact of Magnetic Perturbation

Assume that there is another orthogonal magnetometer triad (MAG2) very close to the first one (MAG1) having its Z axis aligned with MAG1 but with a different orientation for the X and Y axes. Assume this orientation to be 30°. Figure 10 portrays the arrangement of the two triads of magnetometers.

Figures 11(a) and (b) depict the magnetic field profiles of the two sensor triads MAG1 and MAG2, respectively.

Comparing MAG2’s magnetic field profile with the one generated by MAG1, it can be observed that the norm of the magnetic fields are the same for both triads but the individual magnetic field components are different due to their different orientations. It can also be observed in Figure 11(b) that the X axis component of MAG2 is not affected by the perturbation source and is exactly equal to the X axis component of Earth’s measured magnetic field.

This is the most critical observation of this research and it plays an important role in the development of a multiple magnetometer based perturbation mitigation technique. From this theoretical analysis, it can be concluded that: There exists information regarding the presence or the absence of magnetic perturbations in the three dimensional magnetic field components sensed by magnetic field sensors placed very close to each other but arranged along different orientations in space.

MULTIPLE MAGNETOMETER PLATFORM (MMP)

In order to successfully utilize the theoretical findings of the previous section, it is necessary to develop a sensor platform that can aid in collecting the necessary magnetic field data along different orientations. Also, the selection of a magnetic field sensor itself plays an important role in the effectiveness of the proposed perturbation mitigation technique.

Figure 12 illustrates the different types of magnetic field sensors that can be used for pedestrian navigation purposes.

Based on the constraints specific to the context of pedestrian navigation and described in the introduction, three types of magnetic field sensors can be

![Image of Arrangement of two triads of magnetometers](image)

![Image of Magnetic field as sensed by the two magnetometers: MAG1 (a) and MAG2 (b)](image)

![Image of Magnetic field sensors, their sensitivity ranges and possible applications](image)
used for pedestrian navigation. These types are commonly known as magneto-resistive (MR), magneto-impedence (MI), and Hall effect sensors.

Based on the properties of MR substances used for the fabrication, two sub-categories of MR sensor can be defined:

1. Giant magneto-resistive (GMR) sensor, and,
2. Anisotropic magneto-resistive (AMR) sensor.

Some other categories are also appearing but they are still in research phases and hence are not discussed here. GMR sensors have very high sensitivity to small amplitude changes and are very useful for sensing weak magnetic fields. Furthermore this sensor does not get saturated in the presence of very strong fields [10]. This sensor seems to be a good candidate for pedestrian navigation but current fabrication technology is not able to make it direction sensitive. Thus, although very weak fields can be sensed, their direction cannot be accurately identified using this sensor. Another issue with these sensors is the requirement of a bias field (a strong magnetic field) in the vicinity of the sensor to make it operate in its linear region. These limitations reduce the chance of using this sensor for orientation estimation. Maybe in the near future the advancements in fabrication technology will enable the use of GMR sensors for orientation estimation.

AMR sensors are not capable of sensing very weak fields and they get saturated in the presence of strong fields, but they can be very effective for field direction measurements [10]. Moreover, by utilizing an inductive coil in close proximity to the sensing element, the effects of saturation can be effectively removed from the sensor in the presence of strong magnetic fields.

MI sensors are capable of sensing both very low magnetic fields as well as the field’s direction. They also consume far less power when compared to AMR, making them ideal hardware to be embedded in smart phones and handheld devices.

Hall effect sensors are widely used for contactless switching applications. In the past, these sensor elements suffered from sensitivity issues requiring very strong magnetic fields for these sensors to work. This mainly motivated their use for automotive applications which provided this environment. Thanks to the advancements in fabrication technology, the sensitivity of this sensor has improved and researchers have now started using it for orientation estimation by sensing Earth’s magnetic field [11]. This sensor can also be considered as a candidate for indoor orientation estimation in the near future.

For this research, Honeywell’s HMC5843 tri-axis AMR sensor is selected as the primary candidate for magnetic field sensing [12]. Although GMI sensors are superior from a sensitivity and power consumption point of view, due to unavailability of this sensor in a reasonable IC package for hand soldering, it is not regarded in this research.

In order to investigate the dependence of the sensed magnetic field with AMR sensors along different orientations, a Multiple Magnetometer Platform (MMP) is developed. It is composed of 12 tri-axis magnetometers arranged on two orthogonal circles (six magnetometers per plane) in the geometric configuration portrayed in Figure 13.

Figure 14 depicts the complete MMP designed and utilized for this research comprising the two orthogonal non-magnetic plates made out of aluminum carrying six magnetometers each. All of the magnetometers are sampled simultaneously using a custom designed data acquisition system.
DETECTION OF MAGNETIC PERTURBATIONS

Multiple magnetometers can be used to reduce the effects of magnetic perturbations on heading estimates. But before mitigating the effect of magnetic perturbations, their presence must first be detected. This section investigates different sources of information contained in the magnetic field data acquired using multiple magnetometers for detecting the perturbations. To ease the investigation, two magnetometer triads with their Z axes aligned and a 30° rotation angle around the Z axis, as illustrated in Figure 10, are considered. In the presence of a perturbation source, it can be seen that the magnitude of the magnetic field varies from its nominal value, as depicted in Figure 9. Therefore, some information about the presence and strength of the perturbation is contained in the magnitude itself. However, it is quite possible that the magnetic moment, which results from the combination of Earth’s magnetic field and the perturbation sources, changes magnitude but not orientation. This can be derived from Equation (4). Such perturbation sources can be considered as constructive as they amplify the magnetic field without affecting its orientation. On the other hand, if the perturbation sources change not only the magnitude of Earth’s magnetic moment but also its direction, they are considered as destructive. Indeed, the heading estimated using this combination will not anymore be oriented with respect to magnetic North.

In order to distinguish between constructive and destructive perturbations, additional information is required along with the magnetic field intensity. Figure 15 depicts the magnetically derived heading estimates in the absence and presence of a magnetic perturbation. Here it can be observed that the presence of a perturbation source causes an abrupt change in the estimated heading for both magnetometers having a 30° orientation difference. Thus, observing a change in the magnitude of the magnetic field as well as a change in the estimated heading can be utilized for detecting a destructive perturbation source.

Equation (7) directly relates the observed quantities with the perturbation source. Once a destructive perturbation has been detected, the next step consists of mitigating it to improve the magnetically derived heading. This can be done either by using the output of Equation (7) as a weighing factor in the measurement covariance matrix or by utilizing the information contained in multiple magnetometer data. Here, the second approach is considered.

Figure 11 depicts the magnetic field measurements sensed by the two triads MAG1 and MAG2, respectively. Remember that the triads’ X and Y axes are coplanar but there is a 30° rotation angle between the two frames. Although all three axes of MAG1 measure some part of the perturbation source, the X axis of MAG2 is only measuring the unbiased component of Earth’s magnetic field. Thus, by observing the change in the magnetic field components between the two magnetometers, one can identify the best field component and use this measurement for estimating the magnitude as well as the orientation of the local magnetic field vector.

\[ E_B = |B - B_E|\dot{\psi} \]
Equation (8) portrays the general form of the Biot-Savart law [9].

\[
d\mathbf{B}(p) = \frac{\mu_0}{4\pi} \mathbf{M} \times \frac{\mathbf{R}}{R^3}
\]  

(8)

where \(d\mathbf{B}\) is the magnetic field gradient.

It can be observed from this equation that a change in the magnetic field vector depends on two main terms:

- the distance between the origin of the magnetic dipole and the observation point \(p\): the separation, and
- the angle between \(\mathbf{M}\) and the sensor orientation given by a unit vector \(\mathbf{R}/|\mathbf{R}|\).

The variation in the magnitude of the local magnetic field can only result from a change in the separation. Therefore, the latter can only result from a perturbation source. But a change in the local magnetic field orientation can be due either to the user dynamic or a perturbation.

From Equation (7), it can be observed that the perturbation detector is able to distinguish between a change in orientation either due to user dynamics or the perturbation. In cases where the user’s orientation changes in a perturbation free environment, the difference between the measured local magnetic field and the predicted one will be close to zero. This will cause the perturbation detector output to identify a perturbation free zone, which suggests that a variation in the magnetic field components, i.e., computing the field gradient, can be used to identify which magnetometer’s measurement senses the less perturbed Earth’s magnetic field component.

### KALMAN FILTER BASED INDOOR MAGNETIC FIELD ESTIMATOR

This section details the extended Kalman filter based estimator developed for estimating Earth’s magnetic field components in indoor environments.

#### State Vector

The states are the errors in the three orthogonal magnetic field components:

\[
e_\mathbf{B} = [e_{B_x}, e_{B_y}, e_{B_z}]^T,
\]

(9)

where

- \(e_{B_x}\) is the error in the X axis component of the magnetic field,
- \(e_{B_y}\) is the error in the Y axis component of the magnetic field, and
- \(e_{B_z}\) is the error in the Z axis component of the magnetic field.

#### State Transition Model

As the pedestrian moves indoors, the perturbation sources vary randomly with almost no correlation causing a random walk in the local magnetic field, which is modeled as

\[
\begin{bmatrix}
\dot{e}_{B_x} \\
\dot{e}_{B_y} \\
\dot{e}_{B_z}
\end{bmatrix} =
\begin{bmatrix}
0 & 0 & 0 & 1 & 0 & 0 \\
0 & 0 & 0 & 0 & 1 & 0 \\
0 & 0 & 0 & 0 & 0 & 1
\end{bmatrix}
\begin{bmatrix}
e_{B_x} \\
e_{B_y} \\
e_{B_z}
\end{bmatrix}
+ \begin{bmatrix}
w_p \\
w_p \\
w_p
\end{bmatrix},
\]

(10)

where \(w_p\) is the sensor wide band noise.

#### Process Noise Covariance

The process noise covariance matrix, \(Q_k\), is composed of the power spectral density (PSD) of the sensor data along each axis. These PSDs are obtained from the Allan variance analysis of the sensor data [7].

\[
Q_k =
\begin{bmatrix}
S_{p_x} \Delta t & 0 & 0 \\
0 & S_{p_y} \Delta t & 0 \\
0 & 0 & S_{p_z} \Delta t
\end{bmatrix}
\]

(11)

where \(S_p\) is the PSD of the sensor. The unit for PSD of magnetic field sensor is Gauss/\(\sqrt{\text{Hz}}\).

#### Measurement Error Model

This model represents the errors between the measured magnetic field components and the observations obtained by utilizing the best magnetic field component.

\[
e_{z_k} = z_k - H_k e_{B_k}.
\]

(12)

\(e_{z_k}\) is the innovation sequence, \(z_k\) is the observation vector, \(H_k\) is the design matrix containing one row per measurement, and \(e_{B_k}\) is the predicted state. In this case, \(H_k\) is the identity matrix.

If no perturbation is detected (e.g., outdoors in a magnetically clean environment), MAG1 is used for the observation vector, as all the magnetometers sense the same magnetic field components. When a perturbation is detected, the gradients of the magnetic field components measured by the multiple magnetometers are analyzed to identify Earth’s cleanest magnetic field component. Assuming that the X axis component of MAG2 was the cleanest one, as depicted in Figure 1, the Y and Z axis components of the same triad are computed using the

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The magnitude of the estimated magnetic field $B$ and the horizontal magnetic field $B_h$ obtained from the X and Y axis components as given by Equation (13).

$$B_y = \sqrt{B_x^2 - B_h^2},$$

$$B_z = \sqrt{B^2 - B_x^2 - B_y^2}.$$  

The magnitude of the magnetic field and the horizontal magnetic field components are obtained from the last perturbation free estimates of the magnetic field components using the Kalman filter.

Once the errors in the magnetic field components are estimated, they are compensated from the sensor data. The heading is then computed from the magnetic field components compensated for the effect of perturbations.

Using this model, one can estimate the errors associated with different magnetometers caused by perturbation sources. For this purpose, the above mentioned Kalman filter is implemented for all the participating magnetic field sensor triads. This provides an insight into the effects of magnetic perturbations as well as the direction from where the maximum perturbation is generated, which can be further investigated for its usefulness in indoor navigation.

**Measurement Covariance**

The measurement covariance matrix for the three magnetic field components is obtained from the variance of the cleanest magnetic field component by utilizing the law of propagation of variance. For the above mentioned case where the X axis component $B_x$ is the cleanest, the variance of $B_y$ is obtained as

$$\sigma_{B_y}^2 = \frac{4}{(B^2 + B_h^2)}(B^2\sigma_{B_x}^2 + B_h^2\sigma_{B_h}^2),$$  

where the variance of magnetic field $B$ is extracted from the CGRF model.

Similarly the variance of $B_z$ is obtained as

$$\sigma_{B_z}^2 = \frac{4}{(B^2 + B_h^2)}(B^2\sigma_{B_x}^2 + B_h^2\sigma_{B_h}^2),$$  

where the variance and magnitude of horizontal field $B_h$ are obtained using the X and Y axis field components.

**EXPERIMENTAL RESULTS**

Based on the magnetic field surveys conducted in different indoor environments, the cumulative distributions for the perturbations as well as the magnetic heading errors caused by them have been formulated and depicted in Figure 2 and Figure 3.

Table 3—Indoor Error Probabilities for 5 μT Perturbation and 10° Heading Error

<table>
<thead>
<tr>
<th>Error Distribution</th>
<th>Minimum</th>
<th>Maximum</th>
</tr>
</thead>
<tbody>
<tr>
<td>Perturbation</td>
<td>0.57</td>
<td>0.93</td>
</tr>
<tr>
<td>Heading error</td>
<td>0.38</td>
<td>0.8</td>
</tr>
</tbody>
</table>

respectively. Based on these error distributions, it can be observed that different types of environments have different perturbation and heading error distributions. For example, Table 3 summarizes these distributions for a specific perturbation field (5 μT) and heading error (10°). Therefore, the possibility of having a 5 μT perturbation field in different indoor environments ranges from 57 to 93%.

The variations observed in the processed probability distributions for different indoor environments suggest that effects of magnetic perturbations on heading estimates are highly dependent on the type of building construction as well as its usage. In order to assess the effectiveness of the proposed magnetic perturbation mitigation algorithms to improve indoor heading estimates, the magnetic field data collected in a public place of particular interest, the shopping mall, is considered. Indeed it offers a diverse indoor environment with shops, restaurants, and offices, as well as furnished corridors. As the MMP provides magnetic field sensed by 12 triads of magnetometers, a large redundancy is achieved. Here the magnetic field components in a semicircle are utilized for perturbation mitigation and error compensation. This semicircle is depicted in Figure 17.
Using these magnetic field measurements, the perturbation detector is utilized for identifying the component with the least effect of perturbations. This component is then used for estimating the errors in all the participating magnetic field sensors.

Figure 18 depicts the raw data of each previously selected magnetometer component (thin lines) and the corresponding expected Earth’s magnetic field components in those directions (thick lines). Expected components have been derived using the true INS post-processed headings and Earth’s local magnetic field vector extracted from the CGRF model. Only a small part of the trajectory traversed is utilized to provide readers with a better understanding of the underlying processes for identifying and mitigating perturbations.

During this data collection period, the pedestrian is walking fairly straight in the beginning. Then right after the 50 s epoch, a turn (about 27°) is encountered followed by a straight line motion. In Figure 18, it can be observed that near the 40 s epoch, MAG3(Y) is the component least affected by perturbations as it is very close to Earth’s magnetic field component in that orientation. Similarly, before the 45 s epoch and up until the 50 s epoch MAG4(Y) provides the best field component for estimating perturbation errors. From Figure 19, it can be seen that the perturbation detector is identifying large perturbations at the beginning and at the end of this profile. This can also be observed in Figure 18, which shows rapid changes in the measured magnetic field components at these times. These changes are not in correlation with user dynamics as can be seen by observing the expected magnetic field components, hence they are caused by perturbations.

Figure 20 depicts the field gradient outputs for the six magnetic field components. In the beginning of this profile, MAG3(Y) is the component with the smallest gradient. Therefore during this time period, the cleanest measurement of Earth’s magnetic field is considered to be that of MAG3(Y). This outcome is consistent with the visual analysis of Figure 18, which shows MAG3(Y) as being the closest component to the expected field component. Similarly in the middle of the gradient profile, MAG4(Y) is the component with the smallest gradient, which suggests this component to be the best representative of Earth’s magnetic field component. This can again be visually verified in Figure 18.

Figure 21 depicts the trajectories followed inside the shopping mall building. The numbers marked correspond to the starting/ending positions of the walking paths, which are kept outside of the building. These trajectories are estimated utilizing common velocity estimates extracted from the post-processed tactical grade navigation system measurements and the different heading estimates. This computation method was chosen for assessing only the impact of heading errors on the trajectories traversed. Three trajectories were traversed in this building starting from one of the waypoints outdoors, going indoors, and then finishing at another waypoint outdoors. In Figure 21, it can be observed that the perturbations had different impacts on each of these paths. In the trajectory from waypoint 1 to 2, the impact of perturbations can be seen for a long duration. This is validated using the perturbation detector output for the same path that is
depicted in Figure 22. It shows the presence of perturbations for a long time period, approximately 200 s.

In the trajectory from waypoint 2 to 3, strong perturbations are encountered only at the beginning. Indeed observing the path in Figure 21, it can be concluded that these perturbations were severe, causing a large error in the estimated heading, which resulted in a large position bias. Figure 23 depicts the perturbation detector output for this trajectory. It clearly translates to the presence of severe perturbations at the beginning, justifying the inherited errors in trajectory estimates. Finally, the trajectory traversed between waypoints 3 and 1 does not reflect any noticeable impact of perturbations. Upon looking at the perturbation detector’s output, shown in Figure 24, it is quite evident that no severe perturbations were encountered along this path, which resulted in a trajectory with no substantial position errors.

After utilizing the outcome of the perturbation detector, identifying the least affected magnetic field component from the measurements of the MMP, and estimating the errors caused by local perturbations, the trajectory estimated using the corrected magnetic field components shows significant improvement as depicted in Figure 21.

To assess the global impact of magnetic anomalies on the estimation of the magnetically derived heading in a shopping mall, a statistical assessment of the positioning quality with and without applying the novel algorithms to mitigate the perturbation was conducted. Table 4 summarizes the root mean square deviation (RMSD) error statistics for the three trajectories.

Again by comparing these statistics with Figure 21, it can be observed that in the presence of medium perturbations for long durations, the position errors are also of medium magnitude, which is portrayed by the RMSD for the first trajectory.
larly, in the presence of severe perturbations occurring during a short time interval, the RMSD reaches its maximum over all three cases, whereas with almost no perturbations, position error statistics are of the lowest magnitude. This shows how positioning errors encountered indoors due to errors in the heading can be greatly reduced by mitigating the effects of magnetic perturbations.

Figure 25 portrays the heading estimates in heavily perturbed regions with and without the use of the perturbation detector and heading estimator. It can be observed that the effects of perturbation on heading estimates are reduced to a great extent after using the proposed estimator. The maximum error in heading due to perturbations is 212° but after using the proposed detector and estimator, this is reduced to 55°.

It is worth mentioning here that in some situations, the detector fails to properly identify the perturbation type. This can be seen in Figure 25 right after the 150 s mark where an abrupt change in estimated heading is observed. Thus, there are some scenarios that are currently not addressed in this work, e.g., user maneuvers in the presence of a constructive perturbation.

CONCLUSIONS

The effects of indoor magnetic anomalies on Earth’s magnetic field measurement and their impact on the estimated heading were statistically analyzed in diverse buildings. It was found that the effects of perturbations depend on the building construction type as well as its daily usage. Experimental assessment was further elaborated with a theoretical modeling of Earth’s indoor magnetic field using magnetic dipoles. This model is used to conduct simulations for assessing the effects of perturbation and identifying the sources of information that can be used to detect these perturbations. Based on this modeling, a perturbation detector is proposed, which in conjunction with a Kalman filter based magnetic field estimator reduces the effects of perturbations and provides a better estimate of magnetically derived heading indoors. A maximum error reduction of 157° is achieved using the proposed novel algorithm. The corrected heading is then utilized to estimate indoor trajectories. The final analysis confirms that by using multiple magnetometers, significant error reduction can be achieved when compared to using the uncorrected magnetic field measurements of a single triad of magnetometers.

FUTURE WORK

The perturbation detector will be further enhanced to remove the ambiguity between perturbation and user motion detection when a constructive perturbation and changes in the user dynamics occur at the same time. Possible uses of gyroscopes and accelerometers for resolving this issue will be investigated. Finally, the use of the magnetically derived orientation outputs for estimating the errors associated with other sensors will be investigated.

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