Magnetic Field based Heading Estimation for Pedestrian Navigation Environments

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Abstract—Heading estimation plays an important role in pedestrian navigation applications. With the advent of smartphones equipped with MEMS sensors, it has become possible to utilize one’s orientation information along with location. This combination has allowed researchers to investigate provisioning users with orientation aware location based services as well as seamless navigation in different environments using Pedestrian Dead Reckoning (PDR) techniques. Although gyroscopes are considered to be the primary sensors for orientation estimation, the errors associated with these sensors require periodic updates from other sources. In case of small hand held devices, these other sources are accelerometers for roll and pitch estimates and magnetic field sensors for the heading. In order to utilize the magnetic field sensors for heading estimation with respect to some known reference, it is desirable to measure only the Earth’s magnetic field components. Although this is achievable in the outdoors, presence of manmade infrastructure in all kinds of urban environments makes it impossible to sense only the Earth’s magnetic field at all times. These manmade magnetic anomalies caused by electronic devices, ferrous materials, mechanical and electrical infrastructures among others are the main culprits contaminating the magnetic field information. Therefore it is desirable to investigate how one can estimate the heading using magnetic field alone in different pedestrian navigation environments by isolating the perturbed regions from the clean ones.

In this paper, a detector is proposed that can identify the magnetic field measurements that can be used for estimating heading with adequate accuracy. The expected errors in the heading estimates are also output based on the test statistics, which allow the proposed detector to be utilized for sensor fusion and estimation of errors associated with gyroscopes. Real world data is acquired using a custom designed consumer grade sensor platform and a high accuracy reference system. Theoretical analysis and experimental results show that the proposed detector is capable of identifying the effects of perturbations on the Earth’s magnetic field, which provides users with a better estimate of magnetic heading in different pedestrian navigation environments.

Keywords—Pedestrian Navigation; Magnetic Field; Indoor Orientation Estimation

I. INTRODUCTION

Magnetometers are sensors utilized for measuring the Earth’s magnetic field [1]. These sensors have now become small enough to be utilized in pedestrian navigation applications. The magnetic field is a three dimensional quantity and thus an orthogonal arrangement of magnetometers is required to observe it completely. By resolving these three axis measurements into horizontal and vertical fields, one can estimate the heading: the pointing direction of the sensor block with respect to the magnetic North. This heading can be easily referenced to true North with the help of magnetic field models like International Geomagnetic Reference Field (IGRF)[2].

With proper calibration of the magnetometers, it is possible to sense Earth’s magnetic field with significant accuracy, which can then be utilized for estimating heading within a few degrees of true North [3]. This is achievable if the environment is free from magnetic perturbations e.g. outdoor (country side) and airborne (aircraft). But in the context of pedestrian navigation, such perturbation free environments are seldom encountered and additional artificial magnetic fields are present causing magnetic anomalies or perturbations that change the magnetic field vector, which finally leads to errors in the heading estimates exceeding even 100° in some cases [4].

This brings one’s attention to alternate means of heading estimation. Gyroscopes measure the angular inertial forces that can be utilized for estimating the heading with respect to some reference. These sensors along with accelerometers have been used for almost half a century in Inertial Navigation Systems (INS). Such systems are also referred to as dead reckoning systems as the measurements of gyroscopes and accelerometers are effectively integrated forward in time with respect to reference navigation parameters [5]. Similar to the advancements in magnetic field sensors, the gyroscopes and accelerometers are also being miniaturized and are getting a lot of attention for pedestrian navigation applications [6]. With inertial navigation comes error growth due to its integration nature. Thus any errors associated with the sensors are accumulated causing an ever increasing error in the estimated
navigation parameters [7]. For successful dead reckoning, these errors need to be properly estimated. From a pedestrian navigation perspective, some specific constraints may be used for estimating various sensor errors and hence correcting for the accumulated ones [8]. But one very critical navigation parameter cannot be estimated by constraints only. This parameter is heading, which in error causes a position error growth of the third order [9]. Errors associated with gyroscope driven heading can be compensated using the magnetic heading only if the environment is free from magnetic perturbations.

The problem of estimating heading for pedestrian navigation applications can be tackled with the help of sensor fusion [10]. A number of researchers have investigated sensor fusion between magnetometers and gyroscopes to complement their limitations. All of the work done so far revolves around accepting or rejecting magnetic heading estimates by comparing some function of magnetic heading with the inertial one [11, 12].

This paper investigates the parameters contained within the magnetic field measurements to not only detect magnetic field for good heading estimates but also to provide statistical information about the goodness of these estimates. The detector developed in this work depends only on magnetic field measurements. Thus the performance of this detector is independent from other sensor accuracies and hence can be easily integrated with different grades of sensors.

In Section II, the magnetic field information is investigated in detail to identify the parameters that can be utilized for detecting good measurements for heading estimation. Section III discusses the two major approaches taken by researchers for detecting good magnetic heading estimates. The major limitations of these approaches are also identified here. Section IV details the realization of a magnetic field detector for identifying good measurements for heading estimates. Section V is dedicated to the statistical analysis of the proposed detector, which is necessary for characterizing its performance. Finally the effectiveness of the proposed detector is quantified in Section VI using real data acquired in a pedestrian navigation environment.

II. MAGNETIC FIELD PARAMETERS FOR PERTURBATION DETECTION

The Earth generates a three dimensional magnetic field. This field, also known as the total field $F$, 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 $H$, the magnetically derived heading with respect to the true North is estimated as

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

where $B_x$ and $B_y$ are the local magnetic field vector measurements and $D$ is the declination angle with respect to true North as shown in Fig. 1.

From (1), it can be observed that perturbations in any of the horizontal field components will cause the heading estimates to be erroneous. Therefore the horizontal and vertical components of the perturbation field govern the impact of that perturbation on heading estimates.

Further, the impact of magnetic perturbations on the Earth’s magnetic field as measured by a three axis magnetometer can be characterized into four major categories. Although the impact can be due to combination of two or more of these categories, for the sake of understanding, these categories are explained individually here. Fig. 2 depicts the effects of magnetic perturbations that are categorized in the following sub sections. Here $B_x$, $B_y$, and $B_z$ are the magnetic field vector components in clean environments whereas $\epsilon B_x$, $\epsilon B_y$, and $\epsilon B_z$ are the errors in magnetic field components caused by perturbations. $\psi$ is the actual heading with respect to magnetic North while $\psi'$ is the perturbed heading.

The magnetic field parameters identifiable from Fig. 2 are:

- Total magnetic field magnitude $F = \|B_x + B_y + B_z\|
- Horizontal field magnitude $H = \|B_x + B_y\|
- Vertical field component $Z = B_z$
- Inclination angle $I = \tan^{-1}\left(\frac{Z}{H}\right)$

![Figure 1. Magnetic field components and their relationship with true North.](image1)

![Figure 2. Effects of magnetic perturbations on magnetic field parameters.](image2)
A. Perturbation with strong horizontal and strong vertical field components

In case of a strong perturbation in both horizontal and vertical, a number of combinations are possible.

- Magnitude changes along the Earth’s field axis with same ratio.
- Magnitude changes along the Earth’s field axis with different ratio.
- Magnitude changes at different axes than Earth’s field with same ratio.
- Magnitude changes at different axes than Earth’s field with different ratio.

In the first case, the perturbation is considered constructive as it will not cause any changes in heading estimates, which is evident from (1). But the total field magnitude will be different from reference (IGRF). Thus if one utilizes the total field magnitude as means of detecting good heading estimates, such constructive perturbation scenarios will be missed. On the other hand, if one uses the inclination angle as means of detection, this constructive perturbation can be identified. In the remaining three cases, the impact of perturbation will be destructive causing substantial errors in heading estimates. Neither field magnitude nor inclination angle will be free of errors. Hence a combination of total field magnitude and inclination angle can be used for detecting good field measurements if the perturbations fall in this category.

B. Perturbation with strong horizontal and negligible vertical field components

In this case, the perturbation along the horizontal field axis can have two possible combinations.

- Both X and Y field components get affected by perturbation with same ratio.
- Both X and Y field components get affected by perturbation with different ratio.

In the first case, the perturbation has no effect on heading estimates. But in the second case, the perturbation will cause errors. It is worth mentioning here that the total magnetic field will change for this category of perturbation and hence by looking at the field magnitude only, one will miss the constructive perturbation periods. Same can be said for inclination angle as it will vary in this case from the reference one. The magnitude of horizontal and vertical fields can be used for detecting this category of perturbations.

C. Perturbation with negligible horizontal and strong vertical field components

In this case, the heading estimates will not have any substantial errors due to perturbation. Both the total field magnitude as well as inclination angle will vary from the reference (CGRF). Similar to previous category, by looking at the magnitude of horizontal and vertical field components, this category of perturbations can be identified.

D. Perturbation with negligible horizontal and negligible vertical field components

This type of perturbation will give the most reliable heading estimates. In this case, the magnitude of total field, horizontal field and vertical field will be comparable to the reference. Also the inclination angle will correspond to the expected one.

E. Parameters for the four categories

All of these observations lead to the following magnetic field test parameters that can be utilized for detecting good measurements.

- Magnitude of total magnetic field.
- Magnitude of horizontal magnetic field.
- Magnitude of vertical magnetic field.
- Inclination angle

III. SELECTED PERTURBATION DETECTION TECHNIQUES IN USE

Most of the work done so far utilizes multiple sensors (gyroscopes and magnetometers) to detect good heading estimates. Few researchers have investigated the magnetic field alone for identifying good measurements. In this section, some promising approaches are reviewed and their limitations identified.

A. Multi-stage compass filter

In this approach, the authors suggest using a multi-stage filter to reject magnetic field measurements that are affected by perturbations [11]. The primary parameter that acts as a perturbation detector in this case is the magnitude of the total magnetic field. If the difference of the measured magnetic field and a known reference (e.g. IGRF) is within a predefined threshold, then the second stage of the filter is triggered. In this second stage, the gradients of magnetic field based heading estimates are compared with those of the inertial sensors (gyroscopes) for a predefined sliding window. If the difference of these two gradients falls within a threshold, the magnetic heading estimates are considered free of perturbations.

The main limitation of this approach is its dependence on the magnitude of the total field alone, which is the primary trigger for the second stage of this filter. As described in the previous section, there are both destructive as well as constructive perturbations present in pedestrian navigation environments. This approach will reject the constructive perturbations as they do cause changes in the magnitude of the field. Thus the probability of missing good heading estimates will be high in this case. The second limitation is the requirement of heading estimates from inertial sensors. It is quite possible to have a PDR approach using magnetometers and accelerometers only [13]. The dependence of this approach on gyroscopes renders it not feasible for such applications.
\textbf{B. Magnetic field magnitude and inclination angle}

In this approach, the authors suggest utilizing not only the magnitude of the total field, but also the inclination angle, which is formed between the horizontal and vertical field components [12]. Here the horizontal and vertical field components of the magnetic field are measured by the magnetic field sensors as well as estimated using gyroscopes and accelerometers. Magnetic field data is considered usable as long as the difference between measurements and estimates is within a predefined threshold.

The primary limitation of this approach is its dependence on the magnitudes of horizontal and vertical fields as this can lead to rejecting good heading estimates in case of constructive perturbations as described in the previous section. Dependence on using other sensors for estimating the magnetic field components for comparison purposes offers limitations similar to the previous approach.

In light of the above mentioned limitations, it is desirable to investigate a magnetic field perturbation detector that relies only on the information contained within the magnetic field itself. Also the statistical information regarding the heading estimates is not available using these two approaches. This information is necessary to assess the reliability of the heading estimates.

\textbf{IV. REALIZATION OF THE PROPOSED DETECTOR}

The effects of different magnetic field parameters on heading estimates as described in Section II suggest that in order to improve the detection of good heading estimates based solely on magnetic field, all of the four magnetic field test parameters need to be considered, which are the three magnitudes \((F, H, Z)\) and an angle \((I)\).

\textbf{A. Magnitude and Angle based Detector}

A detector is developed, which utilizes Generalized Likelihood Ratio Test (GLRT) for individual magnetic field parameters. The test statistics of these parameters are later combined using fuzzy logic. This detector is hereby referred to as Magnitude and Angle based Detector (MAD).

1) Development of individual detectors

For a window size of \(N\) samples, let the test parameter for total field detector be given by

\[
\{F_M \}_{k=n}^{n+N-1} = \{F_M - F_R \}_{k=n}^{n+N-1},
\]

where the subscripts \(M\) and \(R\) stand for the measurements (ideal) and reference respectively. In reality, the measurements will be contaminated by white Gaussian noise, which leads to the following observation model:

\[
y_k^F = F_k^F + v_k^F
\]

where \(y_k^F\) are the actual total field measurements and \(v_k^F\) the measurement noise.

Let \(H_0\) be the hypothesis for bad and \(H_1\) for good magnetic field measurements. In case of a good field measurement, the total field parameter \(F_k^F\) will be completely known whereas in case of a bad field measurement, this parameter will be contaminated by unknown perturbations. Therefore in case of \(H_0\), the Probability Density Function (PDF) is given by

\[
f\left( y_k^F; F, H_0 \right) = \frac{1}{(2\pi\sigma_k^F)^{3/2}} \exp \left( -\frac{1}{2\sigma_k^F} \left( y_k^F - F_k^F \right)^2 \right), \quad (4)
\]

where \(\sigma_k^F\) is the total field noise variance. Using the Maximum Likelihood Estimates (MLE) for the unknown parameter \(F_k\) in (4), one can replace it by its mean over the sample window of size \(N\) [14]. This leads to the following PDF for \(H_0\):

\[
f\left( y_k^F; \hat{F}, H_0 \right) = \frac{1}{(2\pi\sigma_k^F)^{3/2}} \exp \left( -\frac{1}{2\sigma_k^F} \left( y_k^F - \hat{F} \right)^2 \right)
\]

\[
\hat{F} = \frac{1}{N} \sum_{k=n}^{n+N-1} y_k^F
\]

In case of \(H_1\), the total magnetic field is known. This leads to the following PDF:

\[
f\left( y_k^F; H_1 \right) = \frac{1}{(2\pi\sigma_k^F)^{3/2}} \exp \left( -\frac{1}{2\sigma_k^F} \left( y_k^F - F_k^F \right)^2 \right)
\]

The GLRT for detecting good total magnetic field measurements for a selected test ratio \((\lambda)\) is then given by

\[
\Lambda(y) = \frac{f\left( y_k^F; \hat{F}, H_0 \right)}{f\left( y_k^F; H_1 \right)} < \lambda,
\]

which gives the following test statistics for the total field detector:

\[
\frac{1}{\sqrt{N}} \left( \sum_{k=n}^{n+N-1} y_k^F \right) < \gamma_F
\]

\([\gamma_F]\) is the test statistics threshold given by

\[
\gamma_F = \sqrt{2\sigma_k^2\ln(\lambda)}.
\]

By utilizing (9) and comparing it against a predefined threshold, one can robustly detect the total magnetic field measurements \(y_k^F\) adequate for good heading estimates. Similar detectors can be realized for the remaining three magnetic field parameters, which are summarized below.

\[
\frac{1}{\sqrt{N}} \left( \sum_{k=n}^{n+N-1} y_k^H \right) < \gamma_H \quad \text{where} \quad \gamma_H = \sqrt{2\sigma_k^2\ln(\lambda)}.
\]

\[
\frac{1}{\sqrt{N}} \left( \sum_{k=n}^{n+N-1} y_k^I \right) < \gamma_I \quad \text{where} \quad \gamma_I = \sqrt{2\sigma_k^2\ln(\lambda)}.
\]

\[
\frac{1}{\sqrt{N}} \left( \sum_{k=n}^{n+N-1} y_k^Z \right) < \gamma_Z \quad \text{where} \quad \gamma_Z = \sqrt{2\sigma_k^2\ln(\lambda)}.
\]
2) Combining the magnetic field parameters’ based detectors

One way of realizing a detector that takes into account all of the four parameters is by deriving the joint probability distributions while considering the dependence of different parameters on one another. This would lead to characterization of the joint PDFs, thus making the detector realization computationally more complex. Another approach is to utilize the knowledge about the possible perturbations encountered in pedestrian navigation environments as described in Section II for detection rules. These rules can then be utilized with a Fuzzy Inference System (FIS) to evaluate the combined impact of all four parameters on the accuracy of heading estimates. Fig. 3 shows the overall architecture of the fuzzy combiner for MAD. It is quite evident from (8), (9) and (10) that a number of factors need to be investigated in order to completely describe the proposed detector.

V. STATISTICAL ANALYSIS OF THE DETECTOR

The tuning parameters in the proposed detector can be divided into two categories, one for the individual detectors and the second for FIS. The parameters required for the individual detectors are the measurement variances, the test statistics’ threshold and the sample window size whereas for FIS, the input membership functions (fuzzification), the rule set and the output membership functions (defuzzification) are required.

A. Selection of measurement variances for individual detectors

Selection of measurement variances requires detailed insight into the perturbations that one can expect in different pedestrian navigation environments and their impact on the heading estimates. For this purpose, a detailed data acquisition has been conducted in different environments [4]. Table I summarizes the environmental characteristics for the magnetic field data collection. Fig. 4 depicts the PDF for heading estimates in different environments. Here it can be observed that the outdoor urban canyon environment is providing the best heading estimates whereas the office buildings are the worst with a few errors even exceeding 130°.

Fig. 5 shows the total field perturbation PDFs for different environments. Urban outdoor environment is showing the least perturbations in this case, which suggests good heading estimates. But if one compares the heading and total field perturbation PDFs for Engineering building, it can be observed that although the heading estimates in this environment are the third best overall, the total field perturbations are the worst. This means that one cannot just observe the total field magnitude and decide upon the goodness of heading estimates. More parameters need to be looked into.

<table>
<thead>
<tr>
<th>Name</th>
<th>Construction</th>
<th>Open Space</th>
<th>IT HW</th>
<th>Shops (S)/Offices (O)</th>
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<tr>
<td>CCIT (Office)</td>
<td>X</td>
<td>X</td>
<td>O</td>
<td></td>
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<tr>
<td>Engg. (School)</td>
<td>X</td>
<td>X</td>
<td>O</td>
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<tr>
<td>ICT (Office)</td>
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<td>X</td>
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<td>O</td>
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<tr>
<td>MacEwan (Student Centre)</td>
<td>X</td>
<td>X</td>
<td></td>
<td>S</td>
</tr>
<tr>
<td>Shopping Mall</td>
<td>X</td>
<td>X</td>
<td></td>
<td>S</td>
</tr>
<tr>
<td>Urban Outdoor</td>
<td>X</td>
<td>X</td>
<td></td>
<td>S</td>
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<tr>
<td>(Down town)</td>
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<tr>
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</table>

Figure 3. Fuzzy inference system for MAD.

Figure 4. Heading error PDFs for different pedestrian navigation environments.

Figure 5. Total field perturbation PDFs for pedestrian navigation environments.

TABLE I. PEDESTRIAN NAVIGATION ENVIRONMENTS
Fig. 6 shows the horizontal field perturbation PDFs. Again, the urban outdoor environment is the cleanest followed by the engineering building that has the worst total field perturbations as depicted in Fig. 5. This suggests that it is the horizontal field rather than the total field that gives better insight into the accuracy of heading estimates.

Fig. 7 shows the vertical field perturbation PDFs for the different pedestrian navigation environments. Upon comparing these PDFs with Fig. 5, it can be observed that there is a direct relationship between total field and vertical field perturbations. This is a very critical observation identifying strong vertical field perturbations in pedestrian navigation environments, which suggests that good heading estimates are possible even if the total field magnitude is strongly perturbed. Also (1) suggests that the vertical field perturbations play no role in the heading estimates. Therefore one can give less weight age to the vertical field perturbation while assessing the accuracy of heading estimates.

Similar to total and vertical field perturbation distributions, inclination angle error distributions for the selected environments suggest that the decision of accepting heading estimates cannot be solely made by observing the inclination angle errors as shown in Fig. 8.

As most of the work done so far for detecting good magnetic heading estimates revolves around observing the total magnetic field and inclination angle errors, this analysis of different field parameters with respect to heading estimates further justifies the importance of developing a detector that takes into account all of the available information for detection of good heading estimates.

The measurement variances required for individual detectors are selected from the combined distributions of all the four magnetic field parameters. These are summarized in Table II. Shopping mall data set is not considered for the development of the proposed detector. This environment is later used for experimental assessments.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Variance</th>
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<tbody>
<tr>
<td>Total field (F)</td>
<td>84 $\mu$T$^2$</td>
</tr>
<tr>
<td>Horizontal Field (H)</td>
<td>49 $\mu$T$^2$</td>
</tr>
<tr>
<td>Vertical Field (Z)</td>
<td>99 $\mu$T$^2$</td>
</tr>
<tr>
<td>Inclination Angle (I)</td>
<td>$129.4^\circ$</td>
</tr>
</tbody>
</table>

B. Selection of the test statistics’ threshold for individual detectors

The threshold can be selected based on the relationship between probability of detection $P_d$ and acceptable probability of false alarms $P_f$. The Receiver Operating Characteristics (ROC) curve is utilized for the said [14], which also defines the performance of the detector. Fig. 9 depicts the relationship between the probability of detection and the probability of false alarms for the four detectors.

It is quite evident that the detectors based on individual magnetic field parameters have different performances for smaller thresholds. This is a very important observation and signifies that even if some of the magnetic field parameters are very close to the reference ones (smaller threshold means more agreement between reference and measured parameters),
still these detectors will end up producing more false alarms. For example, the inclination angle based detector has the highest $P_d$ for $P_f$ of 0.2. This observation further signifies the importance of combining the outcome of individual detectors for good heading estimates.

For this work, the $P_t$ of approximately 16% is selected as acceptable false alarms, which leads to different thresholds and $P_d$ for the individual detectors as summarized in Table III.

### C. Selection of the sliding window size

The last parameter required for tuning the individual detectors’ performance is the sliding window size. Fig. 10 shows the ROCs for total magnetic field based detector with different window sizes. The sensor sampling rate in this case is 40 ms, which gives the smallest window size of 40 ms ($N = 1$) and the largest window size of 600 ms ($N = 15$) tested for this analysis. As can be observed from Fig. 10, the changes in window sizes do not cause substantial changes in the detector’s performance. This can be related to the pedestrian’s walking speed, which is 1 m/s on average. Even for window sizes of 600 ms, this speed was not enough to cause substantial changes in the magnetic field test parameter. Therefore it can be concluded that for normal pedestrian walking speed, the effect of the investigated window sizes on detector’s performance is negligible. Same is also found for the remaining three detectors.

### D. Relationship between test statistics’ output and expected heading errors

Fig. 11 shows the relationship between the estimated heading errors and the test statistics’ outputs for individual detectors, which are compared with a predefined threshold depending upon the acceptable false alarms as summarized in Table III. A very critical observation here is that there exists a relationship between the outcome of the test statistics and the accuracy of the heading estimates for individual detectors. Thus these relationships can be utilized for the formulation of membership functions for FIS. The latter are required for fuzzification of the crisp test statistics’ outputs. Table IV summarizes the heading error standard deviations that are achievable with different detectors. These are later used for mapping each membership function (spanning values from 0 to 1) to their corresponding weights in the rule sets.

### E. FIS output membership functions

The selection of output membership functions depends on the application requirements. Here it is assumed that categorizing the heading estimates into good, bad and worse is
sufficient. In order to find a relationship between these three fuzzy outputs and expected heading errors, the thresholds of individual detectors are divided into three equal sets.

The output membership functions’ distributions are then evaluated by keeping under consideration the actual errors encountered in heading estimates for the respective threshold sets. For this purpose, the entire data set except for the shopping mall is considered. The latter is used for evaluating the performance of this detector on a data set not used for tuning purposes. The output membership functions’ distributions are summarized in Table V and shown in Fig. 12.

F. FIS rule set

In order to combine the information contained in individual detectors, a set of rules is required for weighing each detector and mapping the final outcome to one of the output membership functions. As described in Section II, the impact of different perturbation sources on magnetic field parameters are utilized for the said. This leads to the definition of following five fuzzy rules.

1. If $F$ is good and $I$ is good then heading is good.
2. If $F$ is good and $H$ is good then heading is good.
3. If $F$ is bad and $H$ is good and $Z$ is bad then heading is bad.
4. If $F$ is bad and $I$ is good then heading is bad.
5. If $F$ is good and $H$ is bad then heading is worse.

| TABLE V. DESIGN PARAMETERS FOR THE OUTPUT MEMBERSHIP FUNCTIONS |
|------------------|------------------|
| Output MF       | Mean (°)          | Std. deviation (°) |
| Good            | 0                | 2.5               |
| Bad             | 8                | 3                 |
| Worse           | 16               | 4                 |

VI. EXPERIMENTAL RESULTS

For the experimental assessment of the proposed detector, an environment is selected based on its importance for pedestrian navigation, which is a shopping mall. It is worth mentioning here that this environment is not utilized for development and statistical analysis of the detector, thus providing an independent and unbiased source of information for testing purposes. Fig. 13 shows the overall test data collection platform. A tactical grade IMU is used for producing high accuracy reference heading estimates, which are utilized for assessing the performance of the proposed detector. Periodic ZUPTs as well as re-initialization of the system in open sky conditions are performed to constrain the position and attitude error growth. The IMU and magnetic field sensor are synchronized using GPS time. Reference [4] describes this platform in more detail. An optical wheel encoder (tachometer) is also used for accurately estimating the walking speed of the person pushing the test platform with an accuracy of $\pm 4 \times 10^{-3}$ m/s. Fig. 14 shows one of the corridors traversed in the shopping mall for the experimental assessments.

The magnetic field data used for this work is collected using Honeywell’s HMC5843, which is a low cost consumer grade magnetic field sensor with a small foot print [15]. This sensor is hosted by a custom designed Multi-Sensor Platform (MSP), which includes all the necessary sensors required for pedestrian navigation applications as depicted in Fig. 15.

Fig. 16 depicts the heading estimates colour coded with their expected accuracies in the shopping mall environment. In the beginning, the user is walking close to a severe perturbation, which is generated by the automatic doors at the mall entrance causing flip in estimated heading. These heading estimates are successfully detected as unusable by the detector. Heading is detected to be of good and medium accuracies for the rest of the epochs. A few false alarms are also present close to 1700 s epoch. Indeed these heading estimates are within the estimated accuracies most of the times.

Fig. 17 shows the heading estimates in a region with wide corridors. Here most of the estimates are correctly identified with a few false alarms near 1600 s epoch. Fig. 19 depicts the trajectory traversed inside the shopping mall. Here the heading estimates at different epochs are identified by arrow heads along with their respective accuracies as identified by the proposed detector. Most of the estimates are correctly identified to be within $8^\circ$ with a few false error identifications.

Table VI summarizes the overall performance of MAD for the selected test environment. More than 80% of the estimates are correctly detected to be within $16^\circ$ of the reference heading. This result is in accordance with the selected probability of detections for individual detectors as summarized in Table III.
Figure 13. Test data collection platform.

Figure 14. Test environment for experimental assessment of the proposed algorithm.

Figure 15. Multi-Sensor Platform (MSP) for pedestrian navigation applications.

Table VI. Performance of MAD

<table>
<thead>
<tr>
<th>Expected Errors</th>
<th>% of correct estimates</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\sigma &lt; 16^\circ$</td>
<td>83</td>
</tr>
<tr>
<td>$\sigma &lt; 8^\circ$</td>
<td>76</td>
</tr>
</tbody>
</table>

Figure 16. Heading and estimated errors near shopping mall entrance.

Figure 17. Heading and estimated errors in severely perturbed region.

Figure 18. Heading and estimated errors in shopping mall with wide corridors.
Figure 19. Traversed trajectory with pedestrian’s heading and estimated errors inside a shopping mall.

VII. CONCLUSIONS

Magnetic field is an important source of information that can be utilized for estimating heading with respect to a reference frame. But in pedestrian navigation environments, the magnetic field is perturbed by manmade structures, rendering this source of information of limited values for estimating the field. Previous work had been done to utilize this perturbed magnetic field by identifying the acceptable magnetic field regions for heading estimates; however, most of this work either did not fully address the pedestrian navigation environments or relied on other sensors for detection purposes.

The detector (MAD) proposed herein utilizes different magnetic field test parameters that can be analyzed for detecting good magnetic field measurements. Results show that the proposed detector outperforms the detection techniques based on partial test parameters and also estimates the expected errors in heading estimates, which are found to be correct 79% of the time for total detections.

This detector will be utilized to provide measurements along with statistical information for estimating errors associated with gyroscopes. An estimation technique will be investigated utilizing consumer grade sensors for seamless heading estimation in pedestrian navigation environments.

REFERENCES