

Magnetic Field based Heading Estimation for Pedestrian Navigation Environments

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Abstract—Heading estimation plays an important role in pedestrian navigation applications. 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. Therefore it is desirable to investigate how good the heading can be estimated 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, which can be used for estimating heading with adequate accuracy. 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; 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. By resolving the magnetic field into horizontal and vertical components, the heading can be estimated, which is 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).

The heading with respect to magnetic North can only be obtained 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.

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). 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 [2]. 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 [3]. For successful indoor navigation, 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 [4]. 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 [5]. 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 [6]. 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 [7, 8].

This paper investigates the parameters contained within the magnetic field measurements not only to detect magnetic field measurements 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.

II. MAGNETIC FIELD PARAMETERS FOR PERTURBATION DETECTION

The Earth generates a three dimensional magnetic field. This field 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 true North is estimated as

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

where B_x and B_y are the local magnetic field vector measurements. D is the declination angle with respect to true North.

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 tri-axis magnetometer can be characterized into four major categories, which are related to the following magnetic field parameters:

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

By assessing the impact of magnetic field perturbations on the above mentioned test parameters, the quality of the magnetic heading estimates in different pedestrian navigation environments can be quantified.

III. TEST DATA COLLECTION ENVIRONMENTS

In order to assess and characterize the magnetic field perturbations, which is required for the development of a perturbation detection scheme, different environments are selected that can be encountered for pedestrian navigation. These range from urban environments to shopping malls and office buildings. Table I summarizes the environmental characteristics for magnetic field data collection. Fig. 1 shows the overall test data collection platform. A tactical grade Inertial Measurement Unit (IMU) is used for producing high accuracy reference heading estimates, which are utilized for assessing the performance of the proposed detector. An optical wheel encoder is also used for accurately estimating the walking speed of the person pushing the test platform.

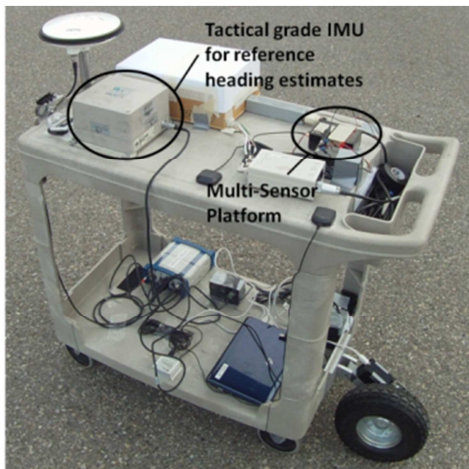


Figure 1. Test data collection platform.

TABLE I.
PEDESTRIAN NAVIGATION ENVIRONMENTS

Environment	Construction		Open Space	IT HW	Shops (S)/ Offices (O)
	Old	New			
Office		X		X	O
School	X			X	O
Office		X	X	X	O
Student Centre	X	X	X		S
Shopping Mall		X	X		S
Urban Outdoor	X	X	X		S

IV. REALIZATION OF THE PROPOSED DETECTOR

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.

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). The generic equation for individual detectors is given by

$$\frac{1}{\sqrt{N}} \left(\sum_{k=n}^{n+N-1} y_k^i \right) < \gamma_i, \quad (2)$$

where N is the sliding window size, y_k^i is the k^{th} measurement of the test parameter, $i \in \{F, H, Z, I\}$ is the parameter under test and γ_i is the test statistics' threshold.

B. 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 each other. Another approach is to utilize the knowledge about the possible perturbations encountered in pedestrian navigation environments for defining the 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. 2 shows the overall architecture of the proposed fuzzy combiner for MAD. It is quite evident from (2) that a number of factors need to be investigated in order to completely describe the proposed detector, which constitutes the statistical analysis of the said.

C. Selection of test statistics' thresholds

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 [9], which also defines the performance of the detector. Fig. 3 depicts the relationship between the probability of detection and the probability of false alarms for the four detectors. For this work, the P_f of approximately 16% is selected as acceptable false alarms. This is done because the individual ROC curves tend to have similar P_d to P_f ratio afterwards, resulting in negligible advantage of combining the four parameters. Different thresholds and

P_d for the individual detectors are obtained for the selected P_f as summarized in Table II.

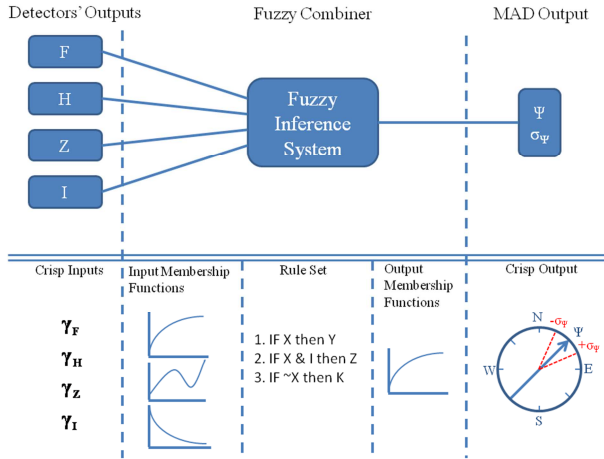


Figure 2. Fuzzy inference system for MAD.

TABLE II.
THRESHOLDS SELECTED FOR THE INDIVIDUAL DETECTORS.

Detector	Threshold	P_d	P_f
F	9.3	0.81	0.16
H	8.0	0.85	0.16
Z	11.0	0.81	0.17
I	10.7	0.81	0.18

D. Relationship between test statistics' threshold and expected heading errors

Fig. 4 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. 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.

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 to visualize the impact of the proposed detection algorithm on heading estimates. 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. As the fuzzy rules as well as the development of the membership functions depend upon the data set available for their evaluation, all the possible environments that can be encountered for pedestrian navigation are utilized for the said except for the shopping mall. 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 shown in Fig. 5.

V. 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.

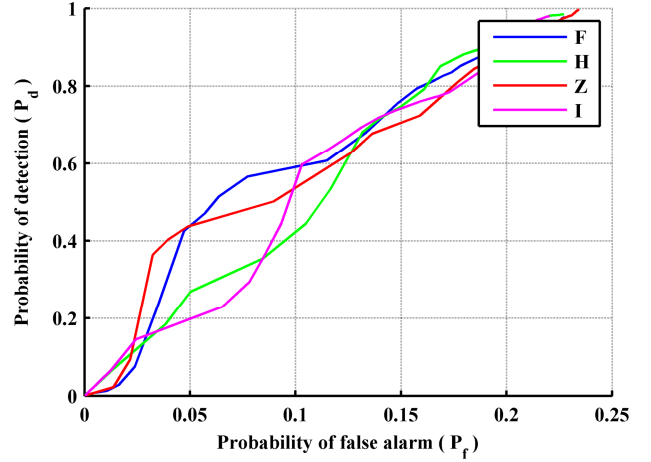


Figure 3. ROC curves for the individual detectors.

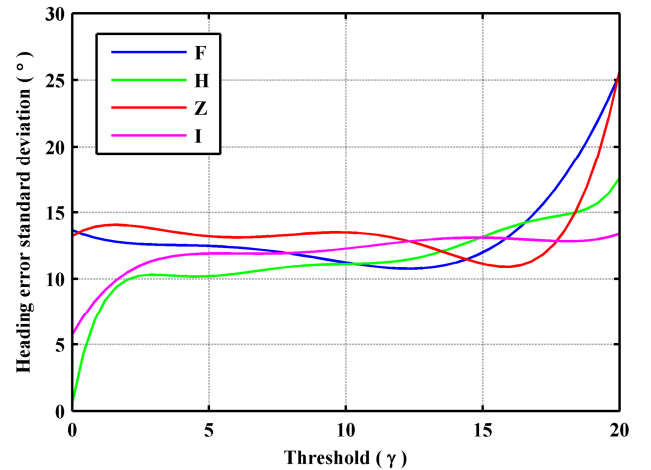


Figure 4. Relationship between threshold and expected heading error.

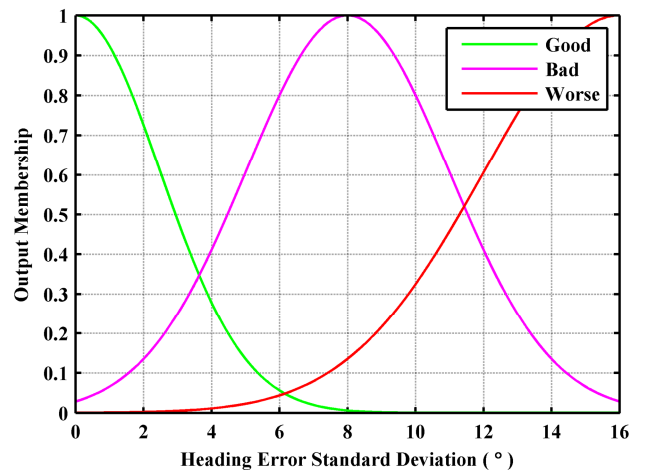


Figure 5. FIS output membership functions.

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 [10].

This sensor is hosted by a custom designed Multiple Sensor Platform (MSP), which includes all the necessary sensors required for pedestrian navigation applications as depicted in Fig. 6.

Fig. 7 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. To improve the visualization of the output of the proposed heading estimator, these are categorized into three groups ranging from good ($\sigma < 8^\circ$) to worse ($\sigma > 16^\circ$). It can be observed that most of the estimates are correctly identified to be within 8° with a few false error identifications.

VI. CONCLUSIONS

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.

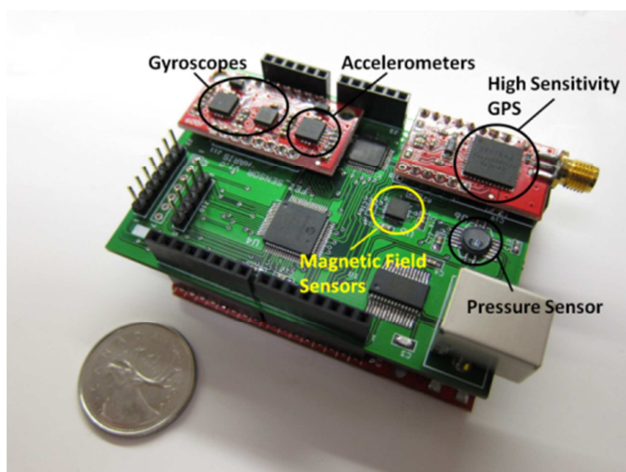


Figure 6. Multi-Sensor Platform (MSP) for pedestrian navigation applications.

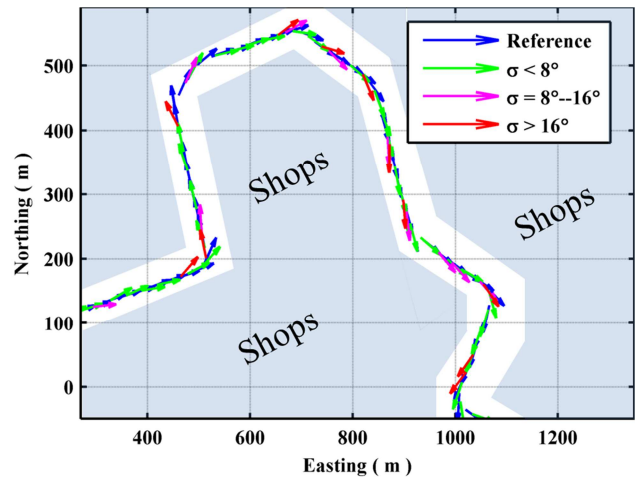


Figure 7. Traversed trajectory with pedestrian's heading and estimated errors in a shopping mall.

REFERENCES

- [1] Bekir, E., *Introduction to modern navigation systems*. 2007, Hackensack, N.J.: World Scientific. xiv, 240.
- [2] Li, D., R.J. Landry, and P. Lavoie, *Low-cost MEMS sensor-based attitude determination system by integration of magnetometers and GPS: A real-data test and performance evaluation*. 2008 IEEE/ION Position, Location and Navigation Symposium, Vols 1-3, 2008: p. 342-350.
- [3] Han, S., J. Wang, and N. Knight. *Using Allan Variance to Determine the Calibration Model of Inertial Sensors for GPS/INS Integration*. in *6th International Symposium on Mobile Mapping Technology*. 2009. São Paulo, Brazil.
- [4] Suh, Y.S. and S. Park, *Pedestrian Inertial Navigation with Gait Phase Detection Assisted Zero Velocity Updating*, in *Proceedings of the Fourth International Conference on Autonomous Robots and Agents*, G.S. Gupta and S.C. Mukhopadhyay, Editors. 2009, IEEE: New York. p. 505-510.
- [5] Farrell, J. and M. Barth, *The global positioning system and inertial navigation*. 1999, New York ; London: McGraw-Hill. xii, 340 p.
- [6] Xue, L., et al., *MEMS-based Multi-sensor Integrated Attitude Estimation Technology For MAV Applications*. 2009 4th IEEE International Conference on Nano/Micro Engineered and Molecular Systems, Vols 1 and 2, 2009: p. 1031-1035.
- [7] Faulkner, W.T., et al. *GPS-Denied Pedestrian Tracking in Indoor Environments Using an IMU and Magnetic Compass*. in *Proceedings of the 2010 International Technical Meeting of the Institute of Navigation - ITM 2010*. 2010. Washington: Institute of Navigation.
- [8] Roetenberg, D., H. Luinge, and P. Veltink. *Inertial and magnetic sensing of human movement near ferromagnetic materials*. in *Proceedings of the Second IEEE and ACM International Symposium on Mixed and Augmented Reality (ISMAR '03)*. Los Alamitos: IEEE Computer Society.
- [9] Hippenstiel, R.D., *Detection Theory Applications and Digital Signal Processing*. 1st ed. 2002: CRC Press.
- [10] Honeywell. *HMC5843 Data Sheet*. 2010 [cited 2010 August]; Available from: <http://www.honeywell.com/sites/servlet/com.merx.npoint.servlets.DocumentServlet?docid=DA9ACFE3C-F7C0-9998-6085-D9D84941499D>