# Indoor Waypoint Navigation via Magnetic Anomalies

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*Abstract*— **A wide assortment of technologies have been proposed to construct indoor navigation services for the blind and vision impaired. Proximity-based systems and multilateration systems have been successfully demonstrated and employed. Despite the technical success of these technologies, broad adoption has been limited due to their significant infrastructure and maintenance costs. An alternative approach utilizing the indoor magnetic signatures inherent to steel-frame buildings solves the infrastructure cost problem; in effect the existing building *is* the location system infrastructure. Although magnetic indoor navigation does not require the installation of dedicated hardware, the dedication of resources to produce precise survey maps of magnetic anomalies represents a further barrier to adoption. In the present work an alternative leader-follower form of waypoint-navigation system has been developed that works without surveyed magnetic maps of a site. Instead the wayfarer's magnetometer readings are compared to a pre-recorded magnetic "leader" trace containing magnetic data collected along a route and annotated with waypoint information. The goal of the navigation system is to correlate the follower's magnetometer data with the leader's to trigger audio cues at precise points along the route, thus providing location-based guidance to the user. The system should also provide early indications of off-route conditions. As part of the research effort a smartphone based application was created to record and annotate leader traces with audio and numeric data at waypoints of interest, and algorithms were developed to determine (1) when the follower reaches a waypoint and (2) when the follower goes off-route. A navigation system utilizing this technology would enable a low-cost indoor navigation system capable of replaying audio annotations at precise locations along pre-recorded routes.**

## I. Introduction

Navigation through an unfamiliar building for persons who are blind or have low vision is a challenging task. It is commonly recognized that significant vision loss can have a detrimental effect on an individual's ability to navigate independently. A survey was conducted of low vision individuals aimed at evaluating the types of activities they did each week and whether there were activities that they wanted to participate in but did not engage in because of navigation difficulties associated with their visual disorder. It was found that individuals with low vision did not participate in 31% of the activities that they would have liked to engage in due to their visual disorder [1].

Most of these individuals have already solved the mobility problem using a cane, guide dog or using their own low vision as an aid, but there is still great difficulty in reading room numbers, nearby signs, or identifying landmarks. For outdoor navigation, visually impaired persons can use a GPS-based navigation device to solve location determination problems. GPS based devices are not useful in a large office buildings where standard GPS receivers rarely can obtain sufficient usable satellite signal to produce an accurate solution. In addition, GPS systems offer no appropriate geographical databases for office buildings.

Numerous technologies have been proposed to construct indoor navigation systems. These approaches include proximity based approaches using infrared transmitters, RFID, retro-reflective IR coded signs and multilateration based schemes including ultrasound, ultra-wideband [2], Wi-Fi and Zigbee radio frequency technologies using receive signal strength (RSSI) or Time-difference-of-arrival (TDOA) and angle of arrival (AoA) to locate the wayfarer.

There is growing interest in the use of the magnetic distortions within steel-frame buildings as a source of localization information [3-6]. Static indoor magnetic fields can fluctuate significantly due to the presence of steel and reinforced concrete and electric power systems. These indoor magnetic anomalies have been shown to be stable over time, and have sufficient magnitude and spatial variability to enable their use in location systems. Magnetic anomaly based systems offer the potential of dramatically lower infrastructure costs compared to existing systems.

Previous works have focused on inferring location by using pre-measured 2D anomaly maps. However, the accurate magnetic survey of a large building represents another potential barrier to adoption. The present work seeks to further reduce financial hurdles to implementation by minimizing the setup costs associated with the system.

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Instead of relying on accurate 2D or 3D magnetic indoor maps the present work adopts a leader-follower approach. A leader gathers magnetic data along a route of interest, adding annotations at points of interest. The follower determines their location along the route by matching the leader's pre-recorded magnetic data. At points of interest annotated in the leader's route the navigation system generates cues to assist the follower. If the follower's path deviates significantly from the expected route the system should alert the user of this path deviation, allowing them to retrace their steps.

By eliminating the requirements of a fixed infrastructure and high implementation costs, the present work seeks an approach to indoor blind navigation that can be implemented by individuals.

## II. Methods

As part of this research subjects instrumented with magnetometers and other sensors walked routes within several large shopping centers. Each route was traversed multiple times to provide one leader and several follower routes for algorithm design and evaluation. This section details the wireless sensors, the logging application and the data collection protocols.

### A. *Sensor Hardware*

Sensor hardware used in the project consisted of small body-worn Inertial Measurement Units (IMUs), shown in figure 1. These units contain three-axis magnetometers, accelerometers and gyroscopes under the control of a microcontroller. Sensor outputs are sampled at 200Hz and transmitted via an integrated Bluetooth interface.

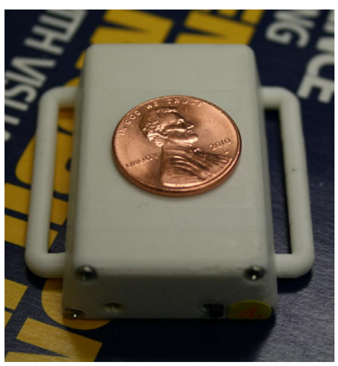

Fig 1. Photograph of the custom wireless IMU used to instrument subjects in this research.

Sensor calibration was performed on the IMUs to correct for scale factor, bias and misalignment. The resulting calibration data is stored onboard on IMU flash memory.

Data collection was performed with a Nexus One smartphone. Data from the phone's integrated magnetometer and accelerometer was also collected during testing to enable feasibility testing to consider smartphone-only solutions.

### B. *Logging Application*

To support the logging of data from the IMUs and the Nexus One sensors an Android application called "IMU Logger" was developed (shown in figure 2.) This application collected and wrote data log files for magnetic and inertial data streamed from paired and active Bluetooth IMUs and the phones internal sensors. Data log files were written to the phones SD card. Log files were written for each sensor unit and the sensor data were synchronized in two ways, each sample was given a timestamp from the Android system associated with its time of collection by the phone. A second timestamp was generated by the sensor unit and consists of an integer that is incremented at each sample. The Android timestamp enables the individual sensor results to be aligned with each other, while the IMU marker provides a reliable timestamp that allows for accurate sensor time integration, and allows dropped packets to be detected. The log files contain uncalibrated sensor readings and were processed into final values during post-processing.


Fig 2. IMU Logger application showing three-axis accelerometer and magnetometer data from the phone and two IMUs.

During data collection the subject was able to add numerical annotations to the stored records by selecting the button with the plus (+) sign in figure 2. At the start of each run, this annotation counter was reset to zero and each press of the button incremented the count. Audio recording was also an annotation option in the logging application. The red and blue buttons represent start and stop audio recording using the device's built-in microphone.

In the lower two-thirds of the screen are displays of the various IMUs that can be recorded. The leftmost column show the phone's internal sensors, while the others are paired Bluetooth IMU devices. This feature allowed exploratory data collection runs with additional body-worn IMU's. Each device can be independently connected or disconnected and can be commanded to stream data or stop. On a Nexus One smart phone, IMU data was successfully logged from 6 IMUs simultaneously while streaming sensor data at 200Hz.

*Data Collection Protocol*

Several indoor sites were selected including the Mall of

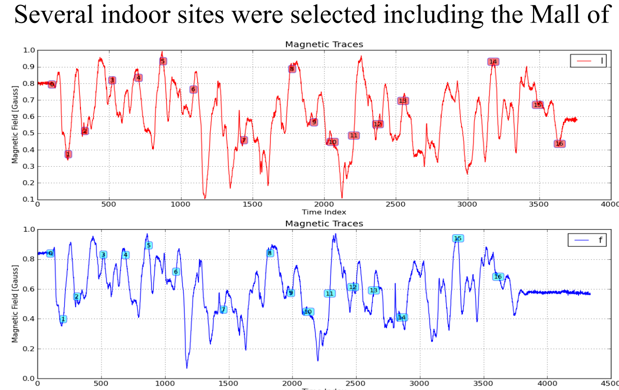


Fig 3. Magnetic data collected at the Mall of America. The leader data is shown above (red), the follower below (blue). Numeric annotations are displayed at the times they were recorded.

America (MOA) in Bloomington MN, and the Rosedale and Har Mar Malls in Roseville, MN. Subjects were instrumented with two wireless IMUs, one attached to their shoe and one attached to the hip pocket. The Android phone was typically held in the subject's hand, under their control to enter annotations. As described in the previous section, annotations insert time-stamped identifiers into each log file. Indoor data collection was performed without the benefit of a secondary localization system to provide independent position estimates. Instead, the subject was instructed to make annotations at fixed locations along their route. In practice annotations were made when passing by the entrance to each shop along their route. Thus the annotations alone provide a means to ascertain the location accuracy of the algorithms developed.

The observed magnetic anomalies exhibited power at wavelengths much smaller than the width of a Mall's corridors. To control for this, subjects were instructed to walk close to the right side of the hallway at a distance gauged to approximate that of a blind walker tapping the wall with a cane.

Multiple routes were established in each Mall. The first pass along each route was considered to be the *leader* route. The route was repeated three more times to gather *follower* data (see figure 3) for use in algorithm development described below.

A typical route started with a brief stationary phase to enable gyroscope bias to be re-estimated to accommodate turn-on bias and thermal effects, if needed. Paths typically required several minutes to traverse, and data was collected during normal operating hours, including busy and crowded conditions, to ensure that realistic dynamic magnetic interference from elevators, escalators, strollers, wheelchairs and route deviations due to crowds were included in the data.

Initial datasets collected at the MOA were used for algorithm development and filter optimization. Additional data was collected again at the MOA as well as other Malls to provide independent datasets to for algorithm testing.

## III. Algorithm Development

Two algorithms were developed with the goals of providing an estimate of when the follower has reached the location associated with an annotation in the leader route and providing an 'off-route' indication. It was assumed that the algorithm should only utilize magnetic and accelerometer measurements; sensor systems available on all smartphone platforms. The two algorithms developed are the Windowed Cost Minimization method and the Continuous Processing Method.

### A. Windowed Cost Minimization Method

This approach uses a least-square cost minimization to score comparisons between the follower window and a candidate master window. After each magnetic magnitude is measured in the following route, the most recent window of samples is compared to a range of samples within the reference leader route, as shown in figure 4. The comparison consists of taking a square root of the sum of the differences between the two squared magnitudes (RMS error). This is done at all possible relative positions between the two windows, and the lowest error found indicates the estimated position within the reference route. This approach proved to be more indicative of the correct position than standard cross correlation, but fails when comparing datasets collected with significant differences in leader and follower speeds. One solution to this problem that was explored uses pedometry to define the window widths, and to resample the data so that comparisons are made in units of estimated steps.

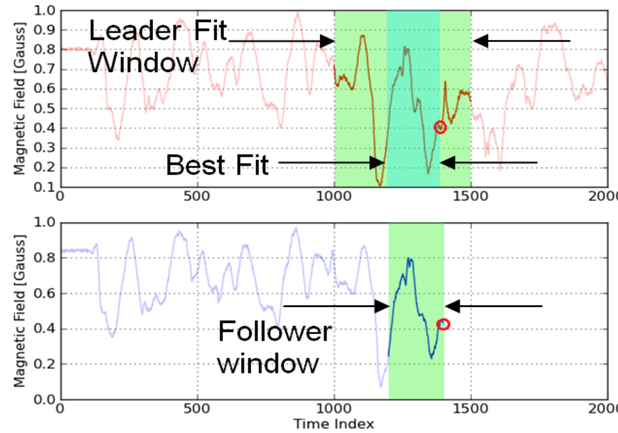


Fig. 4 Windowed Cost Minimization strategy compares recent follower data with a range of leader data to find the best estimate of current position in the leaders' index space.

### B. Dynamic Time Warp Method

The objective of each route-following processing technique is to perform data alignment so that it can be determined if the recorded route follows the reference route or if there were any deviations from the route. Therefore, it is necessary for this data alignment to be accurate and appropriately illustrate where or when there is no possible alignment (during a deviation).

The approach of this data processing technique that was primarily investigated for the magnetic field route-following

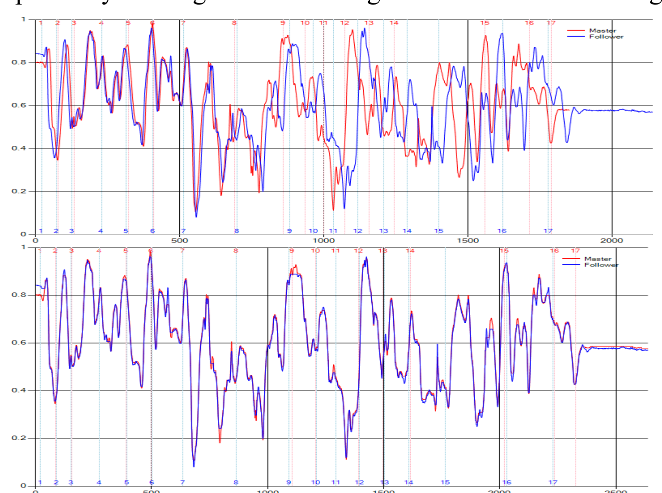

Fig. 5 Leader (red) and Follower (blue) magnetic route data before (above) and after (below) alignment using dynamic time warping (DTW). Good alignment is a measure of how accurately the algorithm can localize the follower in the leader's frame of reference.

research was the concept of the dynamic time warp (DTW) algorithm. Dynamic time warping is part of the Continuous Processing Method (CPM) algorithms that seeks to align sets of data by both index – and time [7], [8]. This process scans two time series and compares their amplitudes throughout. A cost function is created that measures the differences in the amplitudes between the two series as the series' data sets are scanned. The index change that minimizes this cost function is stored and used to adjust the second time series with respect to the first. The recorded time shifts (or index shifts) provides a measure of the path differences when the time (or data index) is correlated with the route follower's position information.

An example of the DTW processing for the magnetic field route-following is provided in figure 5, with the magnetic field magnitude measured at the subject's hip. The top panel shows that the two runs have similar structure in the field magnitudes, but do not line up along the data index axis. The DTW was then used then to process the two runs. The bottom panel shows the result after the time warping and demonstrates how well the technique can align the two series. The good agreement between the leader and follower runs after warping demonstrates the power of the technique, and the feasibility of the route follower concept.

## IV. Off-Route Detection

To test off-route conditions additional data runs were collected which initially followed the expected leader route, but then diverted into stores, across corridors and other ways. Diversions were detected with both algorithms.

The windowed cost method detects off-route deviations when the observed and expected magnetic field plots produce best fits with large costs for some period of time. The high difference between the two vectors, normalized by the number of samples, can be used to observe this deviation. Should the error remain large over an extended period of time, the user can be notified that they are off-route.

The DTW algorithm detects a route diversion through its data scanning process as it determines new data elements do not sufficiently match the reference route when trying to adjust the cost function from its last value. As an off-route diversion continues, such that the mismatch is large between reference and following route, the last value of the processed DTW data is held constant until the end of a run or until new data eventually meets the cost function criteria. Although it is possible that values on a diverted route may appear to match the recorded route, the diversion detection process in coordination with determined distance and heading can validate an on-route path.

## V. Results

To evaluate the performance of the algorithms, an error metric was developed utilizing the recorded annotation time stamps. A final route follower system would detect the follower's proximity to an annotation point recorded in the leader route to trigger navigational cues. Our follower data sets also contain annotations recorded at the same physical locations, providing an objective indication of when the follower is at the same position along route. Since our data collection approach did not record position except at annotation points, time was selected for the error metric. The error metric is measured in the follower's time frame. The error metric measures the time between the algorithm's indication of the follower reaching a leader annotation point, and the time in the follower's data record the same annotation was triggered.

Errors for both algorithms are shown in table 1, along with the variance of the magnetic fields along the route, providing an indicator of the magnitudes of the magnetic anomalies were at each site. The time errors using the both techniques were sufficient to accurate location based navigational cues. Based on estimates of typical walking speeds these errors suggest that this approach is capable of localizing the follower to approximately 1m, well within the requirements of an indoor location system.

TABLE I
Magnetic Route Follower Results

| Location | Routes | Trials | σ(\|B\|) (mG) | COST Error (sec) | DTW Error (sec) |
|---|---|---|---|---|---|
| HarMar | 1 | 6 | 63.1 | -0.45±1.07 | -0.24±0.91 |
| KBT | 1 | 2 | 35.9 | -0.40±0.90 | 0.06±0.40 |
| MOA | 8 | 90 | 146.8 | -0.95±1.38 | -0.90±0.85 |
| Rosedale | 2 | 36 | 94.2 | -1.03±1.77 | -0.86±1.45 |

HarMar = Har Mar Mall, Roseville, MN. MOA = Mall of America, Bloomington, MN, RD = Rosedale Mall, Roseville, MN, KBT = Koronis Biomedical Technology laboratory, Maple Grove MN. COST = Windowed Cost Minimization, DTW = Dynamic Time Warp Method.

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