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Indoor Magnetic Navigation for the Blind

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Abstract—**Indoor navigation technology is needed to support seamless mobility for the visually impaired. This paper describes the construction of and evaluation of a navigation system that infers the users' location using only magnetic sensing. It is well known that the environments within steel frame structures are subject to significant magnetic distortions. Many of these distortions are persistent and have sufficient strength and spatial characteristics to allow their use as the basis for a location technology. This paper describes the development and evaluation of a prototype magnetic navigation system consisting of a wireless magnetometer placed at the users' hip streaming magnetic readings to a smartphone processing location algorithms. Human trials were conducted to assess the efficacy of the system by studying route-following performance with blind and sighted subjects using the navigation system for real-time guidance.**

I. INTRODUCTION

A wide assortment of technologies has been proposed to construct indoor navigation systems for the blind and vision impaired. Proximity-based and triangulation systems have been successfully demonstrated [1] and employed. Despite the technical success of these technologies, broad adoption has been limited due to their significant infrastructure and maintenance costs (for review, see Giudice and Legge, 2008 [2]). The approach explored in this research seeks to solve this infrastructure cost problem by utilizing the indoor magnetic signatures inherent to steel-frame buildings; in effect the existing building is the location system infrastructure.

Indoor navigation technology is needed to support seamless mobility for the visually impaired. Most people who are blind or have low vision can navigate outdoors using a cane, guide dog or their own low vision as an aid, but indoor navigation in large or unfamiliar buildings can be very challenging. To be done accurately, it often requires reading signs, room numbers, building maps, and/or identifying landmarks, tasks which are difficult or impossible for a person with low vision. A significant problem in indoor navigation for the visually impaired relates to orientation information: knowing current position in the building and updating changing position/heading with movement [3]. The biggest challenge to low-vision navigation is not mobility information, awareness and avoidance of obstructions to the path of travel, or in executing routes, but with spatial updating, spatial inference and cognitive map development [4].

II. EXPERIMENTAL METHODS

A. Prototype Hardware

The hardware utilized for both data collection and in the pilot human trials consisted of custom wireless inertial measurement units (IMUs) and Android Smartphones. Figure 1 shows the Bluetooth IMU that was used in this research. Figure 2 shows the data logging application operating on a Google Nexus One smartphone.

B. Data Collection

The focus for the research described here is the tracking of individuals along one spatial dimension, similar to the experimental work on magnetic robot localization by Haverinen *et al.* [5]. Early analysis of indoor magnetic environments demonstrated the spatial dimensions of magnetic anomalies typically have little power on scales less than a meter. With this knowledge, it was concluded that magnetic maps could be reliably collected with a single body-worn sensor located at the experimenters' hip. Differences in height between individuals translated to different sensor-to-floor distances, but a small height offset of a few centimeters was demonstrated to be negligible. The use of one dimensional maps imposes constraints on the pathways walked by test subjects, since the magnetic anomalies vary considerably across the broad hallways within the candidate shopping malls. 1D map data was collected close to corridor walls with the expectation that blind cane users could follow these paths by the periodic tapping of their cane on the walls (e.g., the traditional shore lining technique).

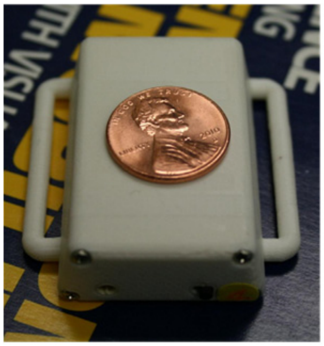
Figure 1: Photograph of the custom wireless IMU used to instrument subjects in this research

Data measurements were made with a custom wireless inertial measurement unit (IMU) shown in Figure 1. This device contains three-axis accelerometers, magnetometers and gyroscopes and can stream data at 200 Hz via a Bluetooth connection to a smartphone or PC. This hardware component was ideal for this application due to its unobtrusive size and its convenient Bluetooth wireless interface. Data collection was made with an Android

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

smartphone processing a custom logging application. Data from one or more IMU's was collected and stored in time-stamped files on the phone's SD card.

The decision to collect data with hip-mounted sensors instead of a cart had one additional drawback. Since the raw IMU data does not supply objective position information, unlike a cart's rangefinder, additional information was needed to enable measurement of a tracking algorithm's accuracy.

To solve this problem an alternative mechanism was developed to insert objective position data into both the map data and the tracking test runs. When gathering data with the IMU Logger application (see Figure 2) the plus-sign button was clicked at each storefront within the candidate shopping mall. This had the effect of inserting a time-stamped numerical waypoint into each IMU log file. The same routes were repeated several times, and each of these trial runs was annotated like the associated map run. Figure 3 shows a map and a trial navigation run together with their numerical waypoints.

During algorithm development magnetic data was replayed within a simulator environment. Tracking algorithms compared the traveler's magnetic data stream to the map trace. The traveler's data was used to estimate their current position within the magnetic map trace. When the algorithm indicated that the traveler had reached a waypoint encoded within the map the relative distance to the same waypoint encoded in the traveler data stream was measured, furnishing an objective error estimate.

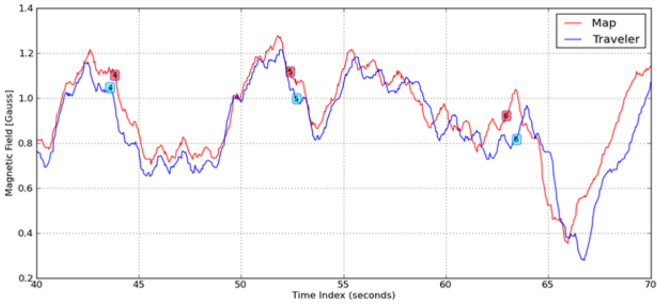

Figure 3: This plot shows a portion of a typical magnetic data map (red) and traveler magnetic data (blue) collected at the Mall of America. Both magnetic datasets are annotated with numeric waypoints corresponding to physical locations (storefronts, etc.) within the Mall. Waypoints were collected by the traveler to facilitate magnetic navigation algorithm development. Candidate algorithm performance was estimated by its *a posteriori* alignment accuracy of the two sets of waypoints.

III. MAGNETIC NAVIGATION ALGORITHMS

Magnetic tracking algorithms are categorically different than triangulation-based location methods used by GPS, GSM localization and many others. Unlike a triangulation-based system, each reading from the user's magnetometer does not contain enough information to solve for location. In practice there will be many locations along a map which share the same magnetometer reading. Magnetic localization must utilize statistical approaches such as Bayesian methods that seek to estimate the user's position on the 1D map in relation to pre-recorded waypoints. Two candidate approaches were considered, a particle filter and a novel real-time variant of the dynamic time-warp algorithm dubbed *incremental dynamic time-warping* (iDTW). Based on performance metrics described above the iDTW was selected for the prototype system. The next sections describe this algorithm in detail.

A. Dynamic Time Warping

Dynamic Time Warping (DTW), part of the Continuous Processing Method (CPM) algorithms [5,6], seeks to align two datasets by time-index. DTW is a pattern matching algorithm used to measure the similarity of two sequences that may differ in their sampling rate. For example, given a signal sampled at a one frequency and the same signal sampled at half of that frequency, DTW would warp in time the samples of the second waveform such that they line up with the first. By warping the sequences in time, the similarity of the two waveforms can be measured independent of time variations. In this application, time independence is very important since the traveler will most likely walk at speeds different than the original recorder of the map sequence, possibly even stopping at unique points along the path.

DTW calculates an optimal solution based on the post-hoc analysis of a two-dimensional matrix built one column at a time as new traveler data is analyzed. Each matrix element in the new column represents the dynamic time warping costs between the current traveler data value and each point in the map. The cost of a given matrix element $C_{i,j}$ is the sum of two terms: (1) the absolute value of the difference in magnetic field magnitude measured by the traveler with index j and the map value with at index i, and (2) the lowest cost value of adjacent elements:

$$C_{i,j} = \left|M_j^t - M_i^{map}\right| + min(C_{i-1,j-1}, C_{i,j-1}, C_{i-1,j}) \qquad (1)$$

The optimal warping solution is determined by inspecting the final complete cost matrix; the lowest cost path is constructed starting at the last column. The indices of the path represent the optimal warped indices for the two series. DTW does well at alignment of map and traveler routes in part because it compares two *complete* sequences from beginning to end. This requirement that the entire traveler dataset be collected before analysis renders traditional DTW unsuitable for this project. Real-time applications require a method to estimate position along the map sequence as the traveler data is collected. In addition, DTW is very memory and processor intensive: the cost matrix can grow very large, as it is an $M \times N$ operation, where M is the number of map samples and N the number of user samples. For magnetometer data which is captured at 50 Hz and maps that take minutes to traverse the storage requirements for this matrix are considerable. A two-minute map traversal would consist of 6000 samples and 6000 * 6000 = 36 million entries in the array. With up to 8 bytes per entry (double precision floating point) the memory requirements for DTW would typically require a workstation, and are not suited for small platforms like a smart phone.

B. *Incremental Dynamic Time Warping*

Due to the shortcomings of traditional DTW, a real-time approach was developed, dubbed *incremental DTW* (iDTW). This approach generates real-time position estimates and greatly reduces DTW's memory requirements. The iDTW algorithm proceeds as follows: as each new data sample is received, a new column of the cost matrix is calculated. Since only the previous column's data is used in the current columns calculation, the memory holding older columns can be freed (or re-used) reducing the memory requirements from $M \times N$ to $M \times 2$ indices. The estimate of the user's position in the map sequence is found using the highest index of the minimum cost within the most recently computed column.

Another optimization was introduced for the embedded computations: a windowed search space for the incremental dynamic time warping algorithm. Basically, costs were computed in a smaller window around the current estimated position instead of computing the costs for the entire length of the map. This bounds the memory and computational complexity to a maximum fixed value per incoming magnetometer reading.

Figure 4 shows the cost matrix of a windowed iDTW cost matrix comparing two sequences of a route recorded at the Mall of America. The windowed nature of the incremental algorithm limits the "height" of cost computations around the estimated position (the darkest portion of the image), reducing the computational complexity of the algorithm. In this example, note that progress of the traveler sequence is slower than that of the map sequence due to the traveler moving more slowly—there is even a period around 80% of the way through where the traveler stopped moving which is clearly evident in the image.

C. *Prototype Navigator*

In this program, a Smartphone application was written to guide blind travelers along a prerecorded route using magnetic anomalies measured by a Bluetooth IMU attached to their right hip. This application implemented the iDTW algorithm described in the previous section, and provided text to speech directions at predefined points along the routes. For the purposes of experimentation, the application also recorded all IMU readings and audio during the entire route traversal for later review and analysis. The Android platform was selected due to the availability of powerful phone hardware and the relative ease of development using the Android tools. The iDTW was coded in Java and tested on an Android 2.3 Nexus One platform. The user interface for the prototype navigator was its audio output. The prototype navigator stored verbal descriptions to be spoken using text-to-speech (TTS) when the tracking algorithm signaled proximity to the given waypoint. Verbal descriptions were created in accordance with the following goals:

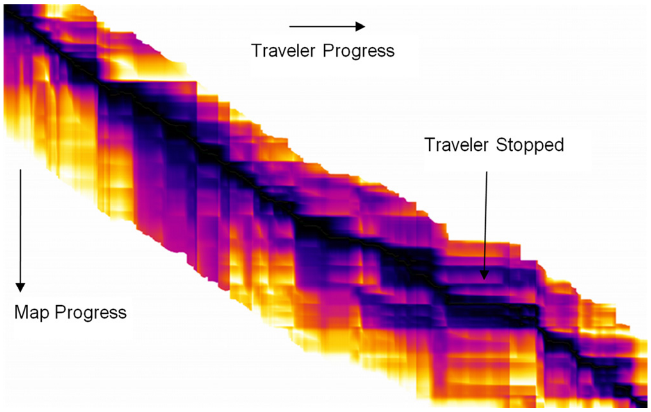

Figure 4: Pseudo color image of the cost matrix of a windowed incremental DTW. Lower cost matrix elements are darker. Only two columns of the matrix are stored in memory at any time, and only the rows of the matrix around the minimum cost position are calculated, reducing the computational requirements of iDTW.

- Provide a consistent set of verbal instructions to describe the environment and all action states for real-time delivery. Provide common terminology and description logic for similar spatial relations and directives, such as turns and obstacle descriptions, when possible.
- Provide terse, compact descriptions that convey the maximal information content using the minimal description length. Based on previous research, we know it is critical to avoid overly verbose verbal cues, which add cognitive effort and undue memory load [2].
- Provide real-time descriptions along the route to facilitate cognitive map development. For this preliminary efficacy testing, this included store descriptions, environmental clues accessible to a blind traveler, and information about all decision points along the route.

The navigator application included some visual display elements to aid debugging. The target magnetic route was plotted graphically on the screen. Once the subject started traveling the route, the incoming readings would be plotted on a strip chart as well as plotted over the map at the estimated position.

IV. PILOT HUMAN STUDY

The feasibility test for the prototype navigator was assessed in a groundbreaking human pilot study. The site chosen for human trials was the Mall of America, in Bloomington, MN. This is one of the most popular shopping malls in the world, drawing 40 million visitors annually to its 500 stores and indoor amusement park. The Mall of America is a challenging environment for the visually impaired, with numerous obstacles to impede mobility while offering few accessibility features. The goal of this test was to demonstrate the utility of our approach in a real-life, challenging environment.

A. *Participants*

Five blind individuals participated in the study in exchange for monetary compensation. Participants (one female and four males, ranging in age from 20 to 48) were either totally blind or only had very limited light perception.

All self-reported as being highly independent travelers. In addition, four sighted controls (two female and two male, representing a similar age range) participated in the study.

B. Procedure

After a practice session where participants were familiarized with the experimental apparatus and task, including a test run with the system with corrective feedback, they began the experimental trials. During the route navigation phase, participants were started at one of the four predetermined route origin locations in the Mall and asked to find a route to a destination target location (a specific store entrance). Route navigation occurred in two conditions (condition order was counterbalanced). In the "System Aided" condition, participants walked along the route with real-time assistance from the system describing what stores they were passing, alerting them to salient landmarks on the route, route deviations (decision points), and describing the actions to perform at these decision points. In the "Unaided Memory" condition, participants received the exact same verbal instructions but rather than hearing them sequentially as they walked the route, the instructions were provided all at once at the route's origin. As such, the unaided memory condition was based on identical information content as the system aided condition, but it was provided off-line (e.g., not in real-time). This condition is similar to what a user might receive from a bystander or description created in advance by a friend, family member, or orientation and mobility instructor. However, owing to its static nature, it differs from the system aided condition as accurate execution requires memorization, mental rehearsal, and spatial updating of the front-loaded verbal instructions and matching of this information with the cues perceived during route travel.

For both conditions, participants used their normal mobility aid during travel to detect and avoid any obstructions (cane users = 3, dog users = 2). The experimenter served as a bystander who could answer questions if the participant got disoriented or felt they needed additional assistance (similar to what might be requested from a random passerby during independent travel). The route terminus was indicated either by the system in the aided conditions or by participant self-report in the unaided memory conditions. For each route, measures of traversal time, number of bystander requests, and correct localization of the destination was scored. A group of sighted participants, serving as controls, also walked the routes under normal visual conditions while using the system to guide them along the route. As they did not know the destination ahead of time, they needed to follow the system's instructions to correctly reach the destination. Performance by the sighted controls provided a "best case scenario" for using the system in a temporally optimally manner and their route traversal data was used as a benchmark for the blind groups.

C. Results

The results provide compelling support for the efficacy of using the system to navigate through our highly complex experimental setting. Where all participants in the unaided memory condition made bystander requests, for a total of 17 requests averaging two per person, no such requests were made in the system aided condition. Comparing the temporal duration required to navigate the routes between conditions also yielded marked differences. Where participants in the system aided condition took an average of 196 s to traverse the routes, the same routes took 273 s in the unaided memory condition. A paired sample T-test confirmed that these differences between conditions were statistically reliable, $T(7) = 2.52$, two-tail, $p = 0.039$. In addition, 100% of the trials in the system aided condition led to correct localization of the route's destination. By contrast, only 20% of the trials in the unaided memory condition yielded correct localization, with 80% of the routes executed in this condition resulting in mis-localization of the route destination. These results demonstrate the importance of real-time information delivery and suggest that, even for seasoned travelers, reliance on memory from offline descriptions is not sufficient for accurate and efficient performance.

Comparing performance between the blind and sighted participants was also informative. The sighted participants took an average of 180 s to traverse the routes. Independent sample T-tests revealed that their performance reliably differed from the blind participants in the unaided memory condition, $T(14) = 4.22$, two-tail, $p = 0.001$, but that it was highly insignificant compared to the blind participants in the system aided condition, $T(14) = 0.67$, two-tail, $p = 0.515$. These results provide clear empirical evidence that blind travelers using real-time route information from our system can perform on-par with their sighted counterparts.

The convergence of statistical performance measures, enthusiasm from the subjects after using the system combined with the unique advantages of magnetic navigation technology suggest that this is a promising technology.

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