On-body multi-input indoor localization for dynamic emergency scenarios:

fusion of magnetic tracking and optical character recognition with mixed-reality display

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Abstract—*Indoor navigation in emergency scenarios poses a challenge to evacuation and emergency support, especially for injured or physically encumbered individuals. Navigation systems must be lightweight, easy to use, and provide robust localization and accurate navigation instructions in adverse conditions. To address this challenge, we combine magnetic tracking with optical character recognition (OCR) in order to provide robust indoor localization. In contrast to typical wireless or sensor based localization, our fused system can be used in low-lighting conditions, smoke, and areas without power or wireless connectivity. Eye gaze tracking is also used to improve time to localization and accuracy of the OCR algorithm. Once localized, navigation instructions are transmitted directly into the user's immediate field of view via head mounted display (HMD). Additionally, setting up the system is simple and can be done with minimal calibration, requiring only a walk-through of the environment and numerical annotation of a 2D area map. We conduct an evaluation for the magnetic and OCR systems individually to evaluate feasibility for use in the fused framework.*

Keywords— indoor localization; navigation; tracking; emergency; imformation presentation; head mounted display

I. INTRODUCTION

In an emergency, evacuees and rescue teams are faced with a number of challenges when navigating a building or indoor environment. Unfamiliar building layouts, smoke, the absence of lighting, disorientation, or a combination of factors can often prevent an individual from completing navigation tasks in a timely manner, resulting in the need for additional rescue operations or increased risk to the individual.

Due to the recent development of smartphones and other sensing systems, researchers have begun build new ad hoc solutions for localization and navigation of indoor environments. Localization of outdoor environments are typically achieved by a combination of sensors such as GPS and compass, but these have limited functionality or usefulness when in an enclosed area, making other means necessary indoors. As such, other types of methods such as sonar and network localization have been implemented with some success [2][9][16][17][20]. However, many of these methods depend on consistent network access or detailed 3D models of the intended environment for navigation.

With the limitations of these methods in mind, we set out to develop a lightweight system that can achieve indoor localization despite loss of power or impaired vision due to smoke or dim lighting. After considering numerous possibilities, we chose a combination of optical character recognition (OCR) and magnetic tracking to implement our localization and navigation algorithms. Simply speaking, we use OCR to recognize text in a user's environment when visual data is available, namely room numbers, and determine a relative position on a 2D floor map of the building. This allows us to determine location without a complex model of the environment and despite sudden changes to the scene. Magnetic tracking via tablet is used when lighting conditions such as darkness or smoke do not allow for computer-vision based localization. Additionally, OCR localization and magnetic tracking can be used interchangeably to compensate for changing environmental conditions, and can be used simultaneously by choosing whichever system has higher confidence. We also conduct and present results of two pilot experiments to determine accuracy for the magnetic and OCR systems. The magnetic system is tested on a variety of data, including localization estimates for an individual in a wheelchair. The OCR system is then tested in different lighting conditions, including nighttime, daytime, and simulated smoke. From this data, we estimate how the fused system would improve tracking in an emergency.

Lastly, navigation information is presented to the user through an HMD, which allows for hands-free operation. An image through the HMD viewing screen showing a user's position localized from a doorplate is shown in Figure 1. An injured person, firefighter that must use rescue tools, or physically handicapped individual can navigate without the use of his or her hands using our system, which is not true for most localization methods that utilize a hand-held device. This intelligent fusion of methods and hardware gives us a number of advantages over other systems in terms of usability, robustness, and simplicity of implementation.

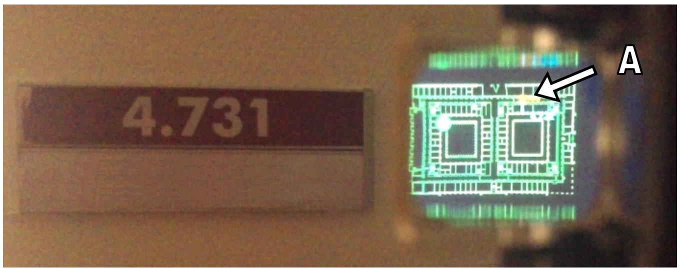

Figure 1. View through HMD screen showing localization (A) on a 2D floor map. The OCR algorithm recognizes door numbers to determine position.

II. Related Work

Related research typically falls into two categories or some combination thereof. These include 1) Methods that can be used to localize an individual indoors using a network or other sensors, and 2) navigation algorithms or strategies and studies regarding navigation tasks in emergency scenarios. The remainder of research tends to focus on training, virtually submersive or simulated environments, or specialized localization or navigation methods for other scenarios.

A. Indoor localization

One of the cornerstones of a good indoor navigation system is the ability to localize the user both consistently and accurately, especially in an emergency situation. There are a variety of methods available for indoor localization, one of which is triangulation based on wireless signals [9][16][17][20]. Since the locations of wireless routers typically do not change in the short term, the position and signal strength of wireless beacons can be used in the same way satellites are used in GPS systems. A hand-held device is then used to calculate position based on the relative signal strengths of each beacon. These methods provide accurate localization, but require advanced registration of the position of each wireless beacon and cannot be used if wireless networks become non-functional, making them more difficult or impossible to use in emergencies.

A second set of localization methods includes sensors that are integrated into a handheld device or other ad-hoc networks. One sensor-based method by Fischer et al. is implemented with foot-mounted inertial sensors and ultrasound beacons [2]. Again, while accurate localization can be achieved, advanced setup of numerous sensing systems is not feasible for all indoor environments, especially large buildings. Methods for generating indoor maps were developed by Xuan et al., who used both magnetometer and accelerometer data to generate maps for later use with navigation [21]. Later, a more flexible, self-contained system based on magnetometers, accelerometers, and optical flow was developed for smartphones in 2012 by Bitsch Link et al. [1]. Using this system, an indoor map can be produced and navigated by calculating the speed of a user and monitoring changes in the magnetic signature of a building.

Prior research shows that wireless sensor-assisted and cyber-physical systems, including networking, distributed control, and knowledge discovery, are becoming increasingly important in managing emergencies [5]. The magnetic tracking we use is relatively similar to these methods, but we improve upon them in several ways, such as utilizing OCR to correct a user's position when localization cannot be achieved from the magnetometer alone. We also discuss several methods for dealing with shifts in the magnetic field or bad sensor data which may differ from original mapping data.

B. Navigation and Other Related Research

The other focus area for this kind of system is on the navigation methods, rather than localization. One such method is presented by Klann et al., which also uses an HMD to present navigation data to a user [11]. In this study, firefighters navigated paths in a building by placing sensor beacons along their travel path. Though firefighters were able to navigate a set path accurately, the system only provides position data where sensors have been placed. Other navigation algorithms have been developed assuming a previous sensor network is in place such as that by Tseng et al. This method can provide navigation paths to multiple exits or emergency events, also utilizing a "hazardous region" concept which allows selection of a safest travel path [20]. Mirza et al. utilizes a similar approach, but for more confined spaces such as homes or smaller buildings. The navigation method takes into account the position of objects for navigation, and assumes a previously existing map of the environment exists that includes locations of objects as well as frequently visited locations. The remainder of research is related to the higher level design of navigation or training systems, simulated environments, or studies on more general aspects of navigation [3][4][12].

C. Further Motivation and Core Contributions

The research discussed above has paved the way for current indoor localization and navigation strategies, but has also uncovered a number of new problems. Some of the most important challenges include simplicity of setup and robustness to environmental changes, both of which are especially important in emergency scenarios. To address these concerns, we propose a system that excels in speed of information presentation, improved localization accuracy during a loss of power or network connectivity, and hands-free usage. We accomplish this by:

- using magnetic localization in darkness or smoke-filled environments,
- creating an OCR based system that can be used when magnetic tracking fails due to unforeseen changes or inconsistencies with the trained database, and
- outlining a simple framework in which localization can occur with minimal setup.

Additionally, we provide general methodology for the improvement of localization in dynamic environments, and provide users with immediate visual feedback. Since our system is hands free, injured people, handicapped individuals, or rescuers that need two hands for other tasks can use the system uninhibited.

III. Localization Framework

The system needs to be as flexible as possible, so we can use the magnetic and OCR components to work both independently of each other and cooperatively depending on context. To outline how the system works, we will first describe each of the individual components in detail, and then specify how the methods can be fused.

A. Magnetic Tracking

In order to accomplish magnetic localization, we first attempted to use an already existing system called IndoorAtlas, which allows users to create and navigate indoor maps [8]. After several tests, we quickly found that this system is prone to error, and does not give direct access to raw magnetic data. The erroneous localization was perhaps due to shifts in magnetic field or sensor data, so we then decided to come up with our own magnetic tracking method to solve these problems. When designing the software, we had several goals in mind, including low time to localization, robustness to shifts in magnetic field, and easy integration with other frameworks, such as our OCR based localization.

1) Algorithm

The first successful method found was to use template matching of a 5 second window of real-time data with a pre-recorded database of magnetic signatures over time. A pilot experiment to test accuracy was conducted in a series of hallways, a total distance of 280 meters. We found that this method produces very high accuracy (above 90%) assuming the user is walking at a constant pace, resembling the results of other systems tested using robots [15]. Note that the results of experiments testing all of our estimation methods are discussed in Section IV. Unfortunately, humans, especially rescuers or evacuees, do not often move in uniform patterns in emergencies. We conducted several initial tests with both the IndoorAtlas application and our template matching algorithm, finding that accuracy decreases greatly when data is recorded at a different speed than the database recording. Some previous methods attempt to solve this problem using optical flow or accelerometers [1][18], but these solutions often require additional sensors, which are not always available and prone to other error. We succeeded at solving some of these problems algorithmically as described below.

2) Shifts in the Magnetic Field

There are typically two types of shifts in the magnetic field that are of concern. One type of shift is due to sensors, which can exhibit a gradual shift over several hours, or shifts that are sudden, but less frequent [18]. The second kind of change is due to equipment or gear a user may be carrying, which we observed when trying to estimate position with a user in a wheelchair. Luckily, none of these kinds of shifts tend to change the general shape of the magnetic field over short windows of time, so we can use simple heuristics to compare against the database with relatively good results. We normalize by subtracting the first value of the comparison window to the first value in the database for every point in time as shown in Figure 2. The normalized input signal is compared using a sliding window algorithm where each window of new data is normalized. We estimate the l1 norm of the difference between each window and the input signal and choose the most similar window in the database.

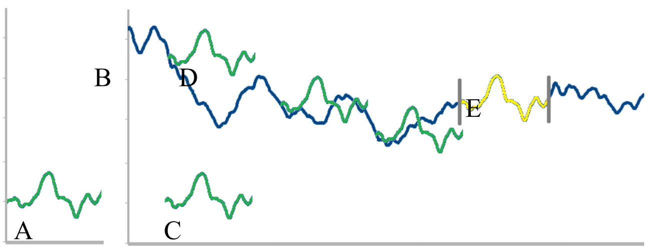

Figure 2. Visual representation of our shift compensation algorithm. A) Test data with a significant shift (green). B) Database (blue). C) Bad comparison if no correction for shift. D) Series of comparisons with shift compensation. E) Correct database segment found (yellow).

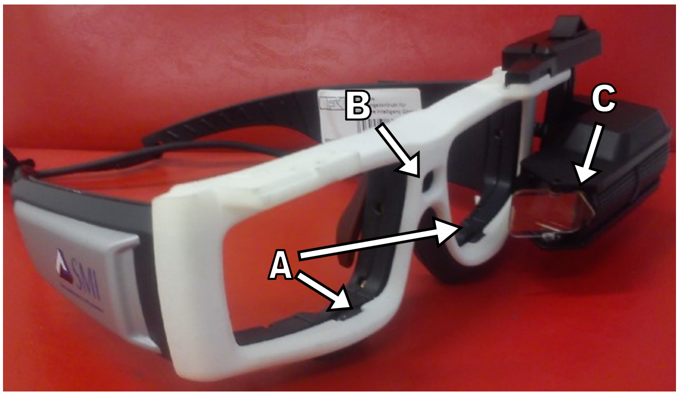

Figure 3. System setup showing A) inward facing cameras, B) outward facing camera, and C) HMD.

3) Shifts in speed

Template matching provides some robustness to slight velocity changes, but unless a user starts moving at a constant speed again, magnetic localization becomes inaccurate. We also implemented a method that replaces outliers with previous values that are believed to be accurate, but radical variations in speed can still prevent accurate magnetic tracking. One could try to solve this problem algorithmically using additional sensors, however, our fused approach already provides a partial solution since users can localize with OCR regardless of speed.

*B. Eye-gaze assisted OCR**

OCR has traditionally been used for applications like digitization of documents, handwriting recognition, and mail sorting. To our knowledge, this is the first attempt at using OCR to localize a user indoors and in an emergency environment. The idea is to annotate a 2D area map in the same way we connect magnetic signatures to positions on the same map. For example, if a user gazed at the door plate of room 103, and that number was recognized by the OCR, we would then update the user's location on the HMD screen. The calibrated camera system and HMD are shown in Figure 3.

Recognition of characters typically works by some method of pattern or feature matching to find an optimal character candidate out of a set of fonts. We make both pre-processing and post-processing modifications to the OCR in order to improve its efficiency and accuracy. Prior to applying OCR, we use a gaze-tracking apparatus that is calibrated to an outward facing camera. Since we know the user's gaze relative to the environment, we know where the user is looking within several degrees of accuracy. In order to improve efficiency, we use gaze to restrict the OCR search window, which improves the time to recognition, and consequently time to localization. The outward facing camera we use is 1280 by 960 pixels in resolution, and the search window is reduced to 320 by 150 pixels, reducing the number of pixels necessary for search by about 96%. If multiple words are recognized, the closest word to the user's gaze is selected. This also reduces the chances of recognizing other nearby environmental text as a false positive reading. The second modification takes place once a raw OCR prediction has occurred. Since there are a limited number of rooms to choose from, we conduct a dictionary search based on the rooms in

*OCR Library by Google: http://code.google.com/p/tesseract-ocr/

the database, and only display a position once the OCR has correctly recognized a full room number. The position is then immediately updated on the HMD viewing screen, showing the user his or her current location on the map.

C. Fusion of Magnetic Tracking and OCR Localization

In general, based on our experimental data, taking the localization estimate with the highest confidence will produce the best results. However, we divided possible system usage into three categories and came up with fusion strategies for each. First is when someone simply needs to reach a given destination. During this time, it is easy for them to travel at constant speed, so the system would use magnetic tracking for a majority of the time, and OCR only when magnetic fails. The second situation includes search and rescue tasks, where someone may have to stop or slow down every so often to listen for survivors or prepare equipment. In this case, magnetic information should be used only when moving between rooms. OCR should be used to confirm position when a user has become disoriented or when a search task has been completed. The last situation is for invasive firefighting or rescue operations. Here, the user will constantly be stopping and changing velocity, so OCR should be used predominantly.

IV. PILOT EXPERIMENTS

To provide a basic evaluation of the magnetic and OCR components, we conducted several experiments that represent different uses of the system. An initial experiment tests the accuracy of our magnetic tracking at constant speeds and with shifts in the magnetic field. A secondary experiment tests the accuracy of the OCR algorithm in various lighting conditions. We then discuss the feasibility of fusing the two methods based on these results.

A. Experiment 1: Magnetic Tracker Testing

1) Setup

Our first pilot experiment was designed to test the effectiveness of template matching with a few different types of data, as well as to test our shift compensation and outlier replacement approaches. We first selected a set of hallways to test against and used an Asus touch screen tablet to obtain data. As the experimenter walked through each hallway, he maintained a constant speed, and recorded checkpoints along the way using a button on the tablet. As he walked, the tablet recorded the current time and x, y, and z components from the magnetic field at approximately 50 millisecond (ms) intervals.

TABLE I. ACCURACY ESTIMATES

Data in Figure 4	Accuracy of Estimates Using Template Matching			
	Source Data	***Compensation for Shift***	***Outlier replacement***	***Accuracy***
B	Constant Speed	No	No	97.62%
C	Wheelchair	No	No	13.94%
D	Wheelchair	Yes	No	60.08%
E	Wheelchair	Yes	Yes	68.30%

The total walking distance used to record the database was 280 meters on a path spanning 7 adjacent hallways. The recorded data was used as a ground truth against which to test localization estimates.

2) Results

To show accuracy, we plot various system estimates versus a ground truth in Figure 4. Additional data to compare against the database was taken by an experimenter at constant speed, and by an individual in a wheelchair. Plot A shows the ground truth, so if our estimate for position p is accurate, it will lie on the same point on plot A at time t.

Our system gives an estimate for every position along the path in each plot. Plot B shows system estimates using a window of data taken from a user walking along the same path at the same speed at which the database was taken, without any shifts in magnetic field. Plot C was estimated using data from the handicapped individual in the wheelchair, resulting in an overall shift in the magnetic field. Simple template matching (C) consequently failed. Plot D uses the same wheelchair data, but using our algorithm that compensates for shifts as described in section III.A.2. As shown, predictions are closer to ground truth, but many outliers still exist. We then replaced outliers with a previous value that has a low standard deviation from other previous values, resulting in the plot in E. Though we still cannot achieve perfect accuracy, the results would still be useful for general localization despite shifts in the magnetic field. Overall accuracy for each plot is shown in Table I. For calculations, a point was considered accurate if it was within approximately 5 meters of the ground truth position along the 280 meter hallway.

B. Experiment 2: Accuracy of OCR in Adverse Conditions

1) Setup

In principle, the OCR module can recognize texts even in an adverse environment, assuming they are printed with ordinary fonts.

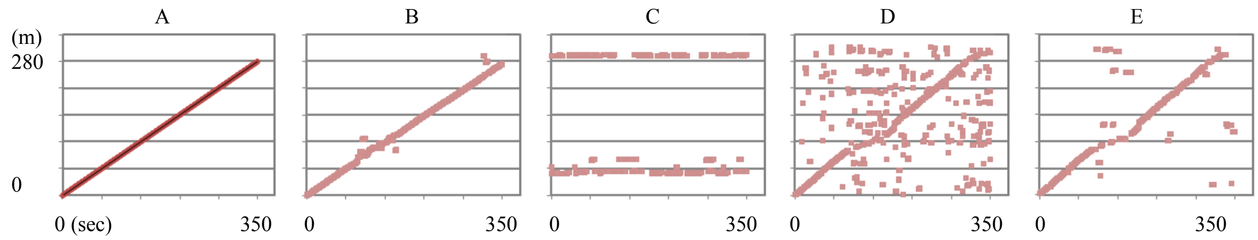

Figure 4. System estimations for user position while traversing a set path. In other words, plots show position (vertical) during a certain time (horizontal). Plots are A) ground truth (actual position), B) constant speed, C) speed is constant but there is a shift in magnetic field, D) the same as C, but with our shift compensation algorithm, E) the same as C, but with both shift compensation and outlier replacement applied.

Figure 5. Door plates in various conditions. Row A is in darkness. Row B is in light. Row C is in smoke and Row D is in heavy smoke. Note that camera exposure automatically adjusted for lighting conditions.

However, the user may need to change his or her perspective by changing the distance or the angle to the text, which means that the text may not be recognized quickly. Several other factors that may affect recognition speed, including illumination changes, perspective changes, interference from smoke, and blur. Our second experiment was designed to test the accuracy of OCR in an emergency simulation. To do so, we tested the ability of the algorithm to recognize a doorplate in various lighting and smoke conditions. A user traversed a single 40 meter corridor with 11 distinct doorplates and gazed at each door plate while walking. He did this in each lighting condition, and the system automatically recorded whether or not each doorplate was recognized. Video of the hallway was recorded as well, and the OCR was tested on simulated smoke. Three doorplates for each condition are shown in Figure. This shows us how long it might take someone, an en-route firefighter for example, to localize using only the OCR while moving and with limited visibility.

2) *Results*

In daytime lighting and light smoke conditions, 6 of 11 plates were recognized. In darkness, only 2 of 11 plates were recognized and only 3 of 11 in heavy smoke. We gathered that a user would have to rely more heavily on magnetic tracking in darkness and as smoke increases.

C. *Discussion*

Through our experiments, we reveal the need to compensate for magnetic shifts. When developing any magnetic tracking system, normalization methods should be considered as a potential solution. We also observed problems with tracking due to changes in speed. This problem could potentially be solved with dynamic time warping algorithms, such as those used for recognizing speech patterns in automated phone systems. Other complementary means for example other signals such as accelerometer and gyroscope or classical signal filtering methods such as nonlinear low-pass, high-pass, and band-pass, Kalman, and particle filters and recent signal processing methods could considerably improve performance and compensate for variable speeds [19]. OCR is more accurate in regular lighting and light smoke, so reliance on OCR should be used based on context. Given the simple nature of our pilot tests, further testing is needed to evaluate navigation tasks in real time by emergency staff or evacuees, which we plan to conduct as future work.

D. *Use in Emergency Management*

There are a number of advantages to using this type of technology during a live emergency. First and foremost, the improved localization of firefighting and emergency staff can assist dispatch and incident command. In addition to knowing the position of rescue teams, camera feedback can be transmitted back to assess smoke density, help remote triage of patients, and allow improved monitoring of the current situation. When a centralized control system is active, an appropriate navigation would be displayed on the HMD. The system could also collect the circumstances of the building from the evacuees and active path planning would also be possible. Our method is also ideal for use in simulations and training exercises, since responders' eye gaze and a corresponding view of the environment can be recorded for post-event viewing and analysis.

If network or communications have been disabled, traversable building paths, camera recordings, and other sensor data can be relayed back to command via radio or when emergency staff returns to the command center. Even if the connection to a control system is not alive, the worn system could autonomously navigate staff or evacuees to an exit. Furthermore, an advantage of our proposed system is that we can rely on several positioning methods, in turn, more reliable localization is possible.

In a more general sense, our system closely relates to the general scheme described in [5]. Cheap handheld devices not only contain the technology for short and medium range communication but also for sensing the environment, which will expand due to improved sensor capabilities in the future. Using a combined a network of stationary and mobile sensor nodes can decrease the infrastructure needs and dependencies of an EMS. Frameworks such as those proposed by Gorbil et al. are necessary for handling the changing networking conditions during an emergency, including the connecting and disconnecting of nodes [6]. Our method could be considered an infrastructure-free localization (sensor only approach), but it could also be thought of as a type of mobile sensor and communication codes. In future systems, these nodes can provide the same services as their stationary counterparts, such as automatically detecting evacuees, rescuers, obstacles and the spread of a potential hazard.

With the spread of smartphones/tablets, robust and stable data and sensor networks can be set up in an ad-hoc manner in emergency situations with a mass amount of dead bodies. Thus this setup has further benefits during a zombie apocalypse since survivors can track the horde or detect zombie-infested areas using their smartphones.

V. Conclusion

We develop a magnetic tracking system and OCR based localization method. Several problems with using magnetic tracking in various environments including shifting and speed variation are revealed, and we provide a solution to shifts using normalization. We then outline appropriate usage of the fused system and show through two pilot experiments that a fused system is feasible for emergency scenarios.

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