Mindful Navigation with Guiding Light: Design Considerations for Projector based Indoor Navigation Assistance System

by
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Executive Summary

People can easily become mindless in their decision-making and become disengaged from their surroundings when their actions depend on information and guidance from an assistive technology. Research has shown how automated navigation assistance systems lead users to be disengaged from the space through which they are traveling, resulting in poor recollection of the environment and poorer situational decision-making. This disengagement and mindlessness can potentially increase the risk of accidents and lower the quality of user experience. If we can help people become mindfully attentive to the environment and surroundings while carrying out navigation tasks using assistive technologies, I hypothesize that we will have better memory of the space, improved cognitive reconstruction of environment, and better understanding of the immediate situation, all of which will lead to better decision making and more efficient navigation.

In this work, I present a new approach for analyzing the problem of navigation assistance for pedestrians, which considers both the physical and psychological constraints of users focused on navigation. I address the physical constraint that eyes should remain "on the street" by providing a new visual interface, named *Guiding Light*, that offers a mixed reality presentation of guidance information in the environment itself, instead of on a screen. We address the psychological constraint that minds should remain engaged with the environment by applying a framework based on mindfulness and mindlessness theory (Langer 1989) in the design of the system. The theory explains how mindsets affect engagement levels and decision-making in daily activities.

In addition, this thesis describes an indoor positioning technology that provides relatively high accuracy localization and heading orientation of a user in indoor environments. The innovation not only involved developing a new sensor but also a software system to collect fingerprint maps and tracking location with the fingerprint maps. This new technology opens up a new area in the field to explore other possibilities of using a magnetic field based positioning system.

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1. Introduction

This dissertation addresses problems related to the development of an indoor navigation assistance system using projector based augmented reality (AR). The contribution includes the development of an indoor positioning system, a user interface for pedestrian navigation, indoor map development, and an analysis of user experience of the system. Particularly, the thesis focuses on two major parts, indoor positioning technology and effectiveness of user interface (UI) for navigation; the two topics cover details of developing a novel indoor positioning system, and examining users' navigation performance and engagement levels while navigating indoor spaces with the use of our system.

Developing an indoor navigation system for pedestrians requires overcoming many different types of problems in engineering as well as in designing user interfaces. Particularly, the thesis focuses on two major parts, indoor positioning technology and effectiveness of UI for navigation; the two topics cover details of developing a novel indoor positioning system, and examining users' navigation performance and engagement levels while navigating indoor spaces with the use of our system. The formal system had to be built due to lack of an effective indoor positioning technology to support such services for personal devices. Tracking an object in a space is not sufficient to provide a real-time guiding service. Localizing an object in 3D space has been an important topic for many positioning technology engineers, but it is more important for a guiding system to identify the direction the user is facing. The information provided by guidance systems can be radically different depending on the facing direction.

In addition, an electronic map is required to support navigational information services. Outdoor maps have been developed by governments and many commercial companies. However, electronic maps for indoor environments may depend on participation by individuals or building owners. It is made worse by the lack of authoring tools and software to support individual users adding multi-layered floor maps. Integrating a high precision positioning system with the map is far from reality in most buildings.

On the UI side, designs for navigation guidance systems need to consider multitasking requirements. Designers need to carefully consider how guidance information is delivered to a user because the user may be in motion, driving, riding or walking; procuring guidance information may be a secondary task. Users may need to divide their visual and cognitive attention to perceive the guidance system and take an action based on it. Voice guidance systems have been developed and widely adopted in car navigation systems to avoid visual distraction. However, many drivers also require on visual (or map) confirmation of the layout of the path they are taking because most drivers depend on visual sensory information as a primary source for navigation. To address these needs, many researchers have been working on the design considerations related to the size of the screen and display method (HMD, windshield display) for car navigation. Similar solutions exist for pedestrians, but they are less effective because of the mobility factor that limits the size of the display. To overcome the limited display resource, various attempts utilizing audible and tactile modalities have been tried (Davis & Schmandt 1989, Holland et. al 2002, Turunen et. al 2007, Erp et al. 2005, Jones & Sarter 2007); these however, do not fully satisfy the users' desire for visual confirmation.

Recently, another important problem surfaced with the use of navigation systems. The past decade of accumulated observation and research (Leshed et al. 2008, Daniel R. Montello, 2009) suggests that navigation guidance systems lead users to be disengaged from the space through which they are traveling, resulting in poor recollection of the environment and poorer situational decision-making. This appears to be true for both vehicle and pedestrian navigation (Holland et al. 2002, Montello 2009, Waters et al. 2011).

I closely pay attention to this problem because a navigation system is one of the first instances of a "smart intelligent" service telling us what to do in order to achieve certain goals. We can imagine delegating tasks to a smart intelligent system, and it may give us a satisfying result. We don't even need to know or care about the details of how the task is handled. If satisfied, no more additional action is required, if not we can ask again. However, when we carefully see in the case of navigation guidance, our constant decision-making followed by action, driving, bicycling, or walking is required while we receive instructions in the course of navigation. Perceiving these instructions is not just a secondary task, but it affects our ability to engage in the task space that we are in. It causes problems as seen in the past decade with navigation systems (Skitka et al. 1999, Leshed et al. 2008). Understanding this problem needs to consider both cognitive / visual attention division and psychological aspects that may cause the problem.

In this dissertation, I present a new approach to analyzing the problem of navigation assistance, which considers both the physical and psychological constraints of users focused on navigation. I carefully look at the physical constraint that eyes should remain "on the street" by providing a new visual interface that offers a mixed reality presentation of guidance information. I also address the psychological constraint that minds should remain engaged with the environment by applying the framework of mindfulness/mindlessness theory (Langer 1989) in the design of the system. The theory explains how mindsets affect engagement levels and decision-making in daily activities.

To explore how the design of the navigational assistance system might alleviate these issues, I built a novel navigation assistance system named *Guiding Light* that uses directions projected in the space itself to help people become better engaged in their environment and task domain. In particular, I focused on indoor navigation, a problem domain which is becoming increasingly important as the size and complexity of high-rise modern building complexes like hospitals, airports and shopping malls increases. The indoor environment is a particularly attractive research domain because there are better opportunities for controlled testing of different approaches to navigational assistance.

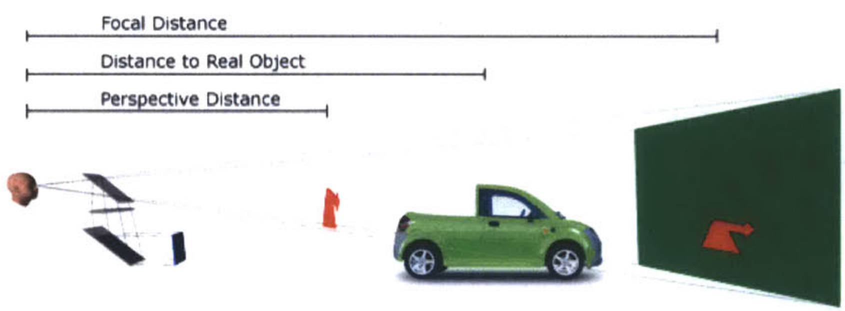
The novel handheld interface, *Guiding Light*, uses a mini projector embedded in the device to project navigational information on the surrounding world. It works with a positioning device that uses an array of sensors to detect its location within a building as well as its bearing. Guiding Light uses an embedded tilt sensor to track the orientation of the phone. This allows us to present different information when the projector is held at different angles or different distances from the projected surface. The core metaphor in this interface is that of a flashlight, which reveals objects and information about the space it illuminates. This interface enables users to retrieve relevant spatial information by pointing the device at particular spaces the users are interested in – for example, directly on the path on which the users are walking.

In the following sections we will analyze the problems of current navigational assistance systems in order to provide a background and rationale for our design strategy. Then, we will provide a detailed description of the Guiding Light design and the architecture that supports it, with a focus on our novel indoor positioning system. Finally, we will revisit our hypothesis along with describing our methodology for evaluation and presenting our results.

2. Background and Related Work

2.1 *Navigation assistance systems considering visual attention division*

Efforts to reduce distractions to our visual and cognitive attention have led to a variety of solutions around alternative representational modalities such as audio and tactile interfaces. David and Schmandt's "Voice assisted automobile system" (Davis & Schmandt 1989) was one of the first systems that assisted users in real-time while traveling. It was designed to let drivers maintain visual and cognitive attention on the street by providing automatic directions audibly. Today, widely used in-car GPS navigation systems employ this audio-based guiding strategy supported by screen-based maps that are automatically updated with the users' location. This combination is designed to reduce secondary work and cognitive loads while driving (Carsten et al. 2001). However, drivers still need to translate auditory information into visual cues, which could cause an additional cognitive burden. Complex instructions might be better represented using simple visual cues, eliminating the need for this translation. Recently, Kim and Dey (2009) explored using augmented-reality (AR) systems to provide visual cues directly on the windshield. This approach can be problematic due to focal mismatching between the AR display and real-world object that could introduce visual confusion (Tonnis, Plavsić & Klinker, 2009).



A number of attempts have been made to develop a real-time navigation assistant system for pedestrians. In contrast to in-car navigation systems that are installed in vehicles, pedestrians must carry the system while moving. The dashboard in a vehicle makes a nice place for the system to be mounted, but researchers have faced significantly more difficulty in designing interfaces for pedestrians. The most technically sophisticated systems use head mounted display (HMD) employing augmented-reality (Steven Feiner et al 1997). This provides a nice way to display directional information while the user's eyes are on the path, but it creates additional problems by obstructing field of our vision (Jansen et al. 2008; Hassan et al. 2007), creating difficulties in focus shifting (Willemsen, Colton, Creem-

regehr, and Thompson, 2009) and burdening users with a cumbersome HMD. Alternative modalities using audio (Holland et. al 2002, Turunen et. al 2007) and tactile interfaces (Erp et al. 2005, Jones & Sarter 2007) allow our eyes to focus on the street, but provide the burden of translating auditory and tactile information into visual representations. Erp developed a system to indicate direction tactilely by vibrating one of several actuators arranged around our neck or waist in a particular direction. However, we still need awareness of the layout of the surroundings and identify the right pathway in order to translate this into action. This awareness requires additional effort using our other senses, i.e. vision, to acquire this preliminary knowledge. A simple directional indicator may be insufficient for navigation tasks in complex pathway layouts, especially indoors.

The most popular way to provide directions for pedestrians is currently to display maps on handheld devices such as PDAs and smart phones. Phone-sized handheld devices provide convenience without the burden of having to constantly wear a device such as a HMD or actuator belt. Although maps or AR on the small screen could provide a just-in-time reference for guidance, the nature of this task – holding up a handheld device to see the small screen (Gartner & Hiller 2007) – could divide our visual and cognitive attention (Bungum & Henry 2005). This makes it difficult for a moving user to use it as real-time assistant system.

We approached the problem of attention division by providing information directly on the surface of the path using small projectors on handheld devices. We suggest that *a personal navigation system that projects guidance directly on the path surface can reduce visual and cognitive attention division.* We designed a system that enhanced our understanding of navigation behavior and cognitive processes. In the process, we identified potential limits of our approach that might direct us toward better interface designs in the future.

In the augmented reality research space, there are a number of projects relevant to this work. Raskar (Raskar et al. 2003) introduced the concept of AR on objects, which reveals information on the surface of the object by augmenting it with information through projection. This research focused on engineering aspects such as how an enhanced projector can determine and respond to the geometry of the display surface, and can be used in an ad-hoc cluster to create a self-configuring display. More recent work known as Sixth-Sense (Mistry & Maes 2009) also utilizes wearable mini projectors on chests to provide information augmented on the surfaces of held objects (or a wall in the front). Sixth-Sense adds a hand gesture interface to provide rich interaction with the investigated everyday objects and the information augmented. Our work adds the aspect of how the augmented information can leverage the engagement and attention level of users when information is projected directly in the task domain, specifically navigation.

2.2 *Guidance design considering mindlessness and mindfulness in navigation tasks*

"Even when information is being fed back to them (Nav-assist users), such as road signs that suggest they're on the wrong route, they won't believe it." (By Tanith Carey, The Mirror 2008)

Automated procedural and decision aids may in some cases have the paradoxical effect of increasing errors rather than eliminating them. Results of research investigating the use of automated systems have indicated the presence *automation bias,* a term describing errors made when decision makers rely on automated cues as a heuristic replacement for vigilant information seeking and processing (Mosier & Skitka, 1999). Although psychological effects of automated navigation guidance systems such as overreliance and automation bias have not been widely applied in the design of the systems, we believe that using these results to inform designs will reduce poor decision-making and disengagement.

When a specific instruction is given by a trusted authority, most people become submissive and instinctively obey only instruction without thinking. (Langer 1989) This result in an effect called "overreliance", in which users become dependent on a potentially faulty authority for instruction. ("Automation and human performance", Moiser and Skitka 1996) Instead of paying attention to the task environment to autonomously solve problems, people selectively choose or ignore stimulus that falls outside the given instructions.

Skitka et. al (1999) conducted an experiment at NASA to learn how an automated guidance system affects the user's performance and errors. The experiment was to measure the performance by asking the subjects to navigate paths in appropriate speed and altitude that were given in the flight manual prior to the aviation task. Deviations from the paths, speed and altitude were considered to measure the flying performances of the subjects. The result shows that when the correct respond rate (speed and altitude adjustments on a path) was higher among those who used the automated assistance (83%) as compared to volunteers relying solely on instruments (72%). On the other hand, despite the presence of a 100% reliable alternative (gauges), much higher error rates were observed when some of the prompts were not presented. Computer-aided subjects showed a respond rate of 59%, while the response rate among volunteers relying solely on instruments was 97%. The later study of Burdick et al (1999) applied a psychological treatment to address the problem, and showed that subjects who perceived themselves as accountable were significantly less likely to fall victim to automation bias in a simulated cockpit environment. This result suggests that performance can be improved and errors reduced by changing the operator's mindset. Making users believe that they are more accountable, however, could burden them with responsibility, causing them to avoid using the system.

A different study about the importance of one's mind-set was conducted by Langer on female room attendants at hotels. Some of the subjects were informed that their job was good exercise and constituted and active lifestyle for them, while other subjects were given no such information. After four weeks, the informed group perceived themselves to be getting more exercise than before and showed a decrease in weight, blood pressure, body fat, waist-to-hip ratio, and body mass index in comparison to the control group.

Her theory suggests that overreliance and automation can be framed as symptoms of *mindlessness*. Langer suggests that whether people engage in tasks mindfully or mindlessly affects their cognitive performance, decision-making, health, creativity and learning, and level of engagement.

The characteristics of mindlessness are: automatic behavior, attention to structure rather than conscious attention to content (Langer, Blank, Chanowitz 1978), and acting from a single perspective. The roots of the mindlessness are repetition, over-learning (Langer, Weinnman 1981), and premature cognitive commitment (Chanowitz, Langer 1981).

Mindlessness can be seen in a variety of different processes. For instance, we might selectively pick cues that fit our preexisting thought process from incoming stimuli, and filter or ignore others when making decisions, resulting in poorer decision making. Mindlessness can be the result of excessive repetition, which causes a rigid relationship between signal and response.

Mindlessness can be avoided by actively noticing differences in an impression or a piece of information, creating opportunities for decision-making, and actively participating in decision-making, all of which increase one's engagement and awareness of context they are in. Mindfulness is characterized by flexibility in handling information, which positively affects our decision-making, response time in changed context, memory, and creativity (Langer & Moldoveanu, 2000). It predicts that people become engaged when they are aware of different ways to achieve a goal and when they feel they are in control over making choices. In this work, we attempt to apply Langer's theory to navigation by occasionally offering users alternative rout choices.

2.3 Positioning Systems

An indoor navigation provides a controlled environment for testing the design of a navigation system, independent of constraints like weather, and lower accident risks during an experiment. The position of landmarks and complexity of routes can be easily controlled in indoor navigational experiments. Working indoors also gives us control of lighting conditions which is important because of the low brightness of current generation of hand-held projectors. In addition to the advantages provided by a controlled environment, indoor navigation assistance system is desirable on its own as the internal structure of buildings becomes larger and more complex and traditional positioning systems like GPS are usually unavailable.

Positioning systems are a core technology in mobile computing to provide the foundation for context aware services, and there exist many such commercially available positioning technologies.

For outdoor environments, GPS is a widely used positioning system that relies on signal time-of-flight between orbiting satellites and a receiver. The technique does not provide orientation measurement, but moving direction can be inferred from a sequence of position updates. Unfortunately GPS requires line of sight between the receiver and the satellites in order to provide accurate position. Thus the technique does not work well indoors (Kaplan 1996).

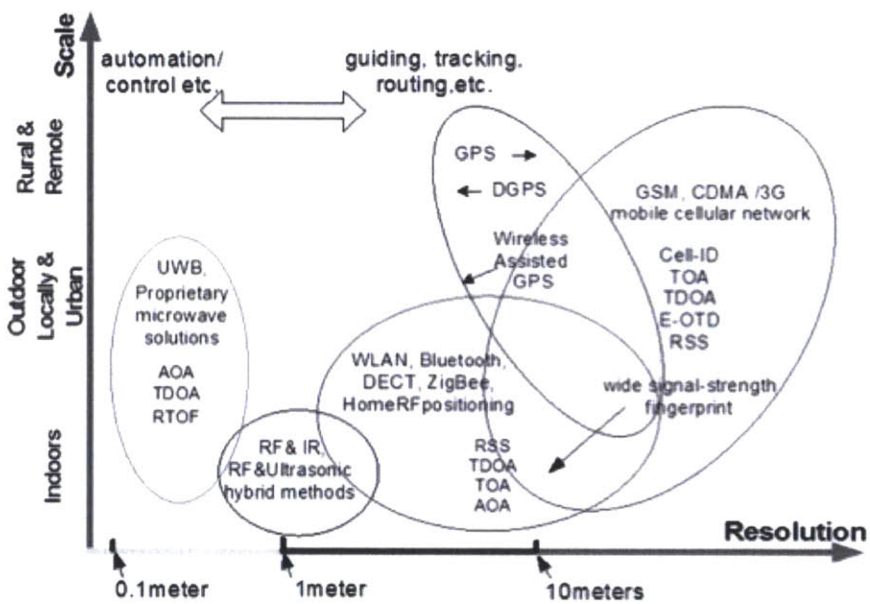


Figure 2.1 Outline of current wireless-based positioning systems (Liu et al. 2007)

There are a few existing technologies that can provide indoor positioning information. The first indoor badge location sensing system, Active Badge (Want et al. 1992), was introduced by Want et al. in 1992. Want developed a cellular proximity system that uses diffuse infrared LEDs which emit unique identifier periodically. The signal is picked up by nearby infrared sensors around the building to identify location of the badge. A descendent system, Active Bat (Ward and Hopper 1997) uses ultrasound time-of-flight lateration to measure an object's location within 9 cm of its true position for 95 percent of the measurements.

Recently, the most popular and inexpensive technology is Wi-Fi (802.11) based positioning. This approach uses two methods for localization; triangulation by measuring signal strength or time of arrivals from known access points (APs), and a fingerprint method to measure relative signal strength from nearby APs when the positions of the APs are unknown. The fingerprint method relies on a map of fingerprints (RSSI distribution) of corresponding locations in order to infer location. (Kaemarungsi et al. 2004, LaMarca et al., 2005, Liu et al. 2007)

While the technologies mentioned above require specific types of devices installed in the environment, computer vision based positioning systems (Karlsson et al. 2005) use visual information in the environment to map and track positions. Through optical input devices, such as a camera, visual features are extracted as spatial references, forming a 3D map. Newly acquired visual features are compared with the map to infer location and camera orientation. These systems can provide centimeter level accuracy, but the main disadvantage of vision based tracking is the computation power required. It can be difficult to run in real-time on power constrained devices such as mobile phones.

Positioning System	**i)Direction**	**ii) Accuracy of positioning**	**iii) Computation & Latency**	**iv) Portability & Infrastructure**
IR beacons based	Fair (require more infra structure)	Great (1-2 meters)	Great	Poor
802.11 RF based	Poor (no direction provided)	Fair (3-5 meters)	Fair	Good
Magnetic based	Good (compass)	Good (2 meters)	Good	Good
Vision	Fair (Large corpus of image features required)	Great (less than meter)	Poor	Poor

Using a single electronic compass (that measures in only one plane) mounted on a robot, Siiksakulchai, Thongchai, Wilkes, and Kawamura (Suksakulchai et al. 2000) developed a localization system using the heading information of a magnetic sensor. Their system collected data and compared the experimental headings to what they actually should have been. At each location, they used the heading error from the current data as well as that from nine previous data points to create a distinctive signature that was then stored. This approach limits their work to localization only in corridors as the robot had to first pass through the same nine points in order to accurately recognize a location's signature. The benefit was that, initially placed anywhere, their robot could eventually determine its position. It requires small computation time and little use of memory in order to get the robot recognize its location.

Haverinen and Kemppainen (2009) used a very similar approach - equipping a robot with a single magnetic sensor that measured in all three planes. They ran their robot through a corridor and had it collect data at set locations to create a map of the hallway. They used Monte Carlo Localization (particle filter) to accurately determine its location from any starting point. Maximum error was about 28 centimeters, though on average the robot needed to travel 25 meters in order to localize itself.

Navarro and Benet (2009) extended the idea of magnetic mapping to a two dimensional area, using a single magnetic compass that measured in one plane. In order to create the two-dimensional map of the magnetic field, they relied on odometry to associate a certain location with unique magnetic readings. They treated the magnetic field as a continuous function in order to estimate magnetic field data at un-sampled points through bilinear interpolation. Then, running the robot in the environment, they used the current data about the magnetic field (and no data memorized from previous timesteps) to compare to the magnetic map to successfully correct positioning errors due to odometry failings. In our work, we tried to investigate a self-localization approach that does not use odometry or any other model that is difficult to obtain from pedestrian motion.

3. Guiding Light

3.1 Why projected AR for navigation for guidance?

One of our goals of using projection-based AR in navigation is to provide users with a real-time navigational guidance while keeping their eyes on a path. It is important for pedestrians' safety that they are not visually distracted while walking along a path. The use of projection-based AR may help users to be more attentive to their surroundings and remaining actively engaged in the world around them.

Projection-based AR guidance on a path can be more direct and intuitive than audio or tactile based guidance. Although audio interfaces for in-car navigation assistance systems have been successful in keeping drivers' eyes on the road because modern road systems have well-defined rules, names, and signs, which make it easier to construct a voice "command" based guidance system, it is more challenging for pedestrian navigation because paths for humans are more complex and less constrained for audio instructions. In addition, audio guidance systems, whether in the form of language or symbolic audio cues, require additional cognitive processing to convert these symbolic directions into visual information to use in identifying paths and layouts. With projected AR, complex instructions might be better represented using simple visual cues, eliminating the need for this translation.

In addition to the advantages of the use of visual guidance, AR may promote interactivity with the surrounding environment. The nature of projection based AR is to illuminate projector light onto a surface of an object. The way a user illuminates projection onto a surface may function as an interface for controlling augmented information. This idea may provide richer interface than simply augmenting a light of information on a surface.

In the following sections in this chapter, we will describe our approach for designing Guiding Light and present example scenarios and prototypes that we have built in the iteration process of designing and building Guiding Light.

3.2 Design approach

A. Augmenting information strategy: abstract versus concrete

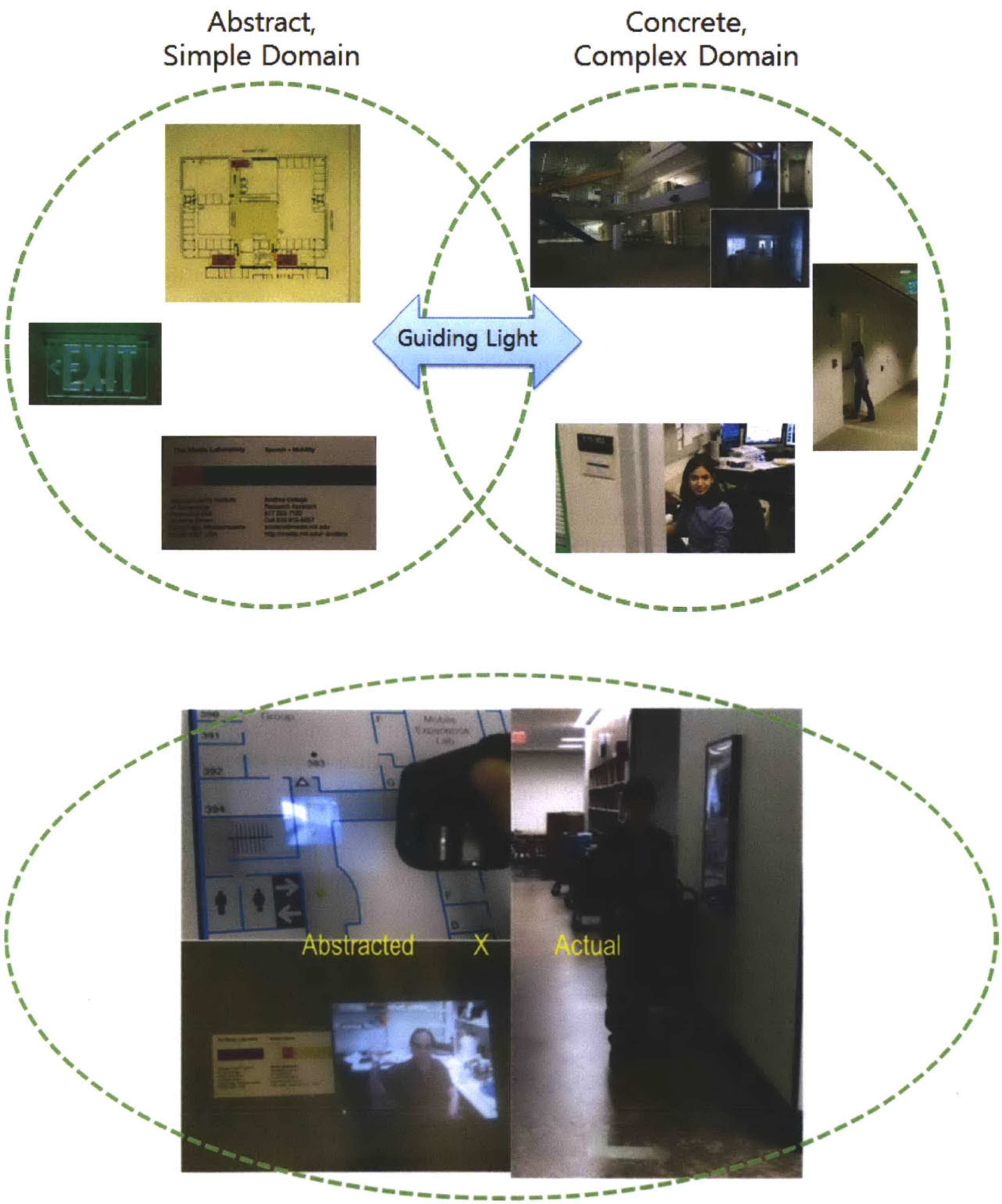


Figure 3.1. Conceptual Aspect of Guiding Light System

The general goal of the system is to provide way-finding assistance. However, extended from this general purpose, the goal of Guiding Light using projection based AR is to i) provide rich and concrete information in the context of simple abstract representations (for example, a photo of a person projected next to their business card), and to ii) provide simple, abstract representations in the context of the concrete, complex world (for example, arrows projected on the ground). Figure 3.1 illustrates the concept behind Guiding Light.

Typical maps show only simple representations of the complex world. Sometimes, these representations are too abstract for people to find easily their way. In contrast, since the real world has a lot of information, representations can easily become too complex.

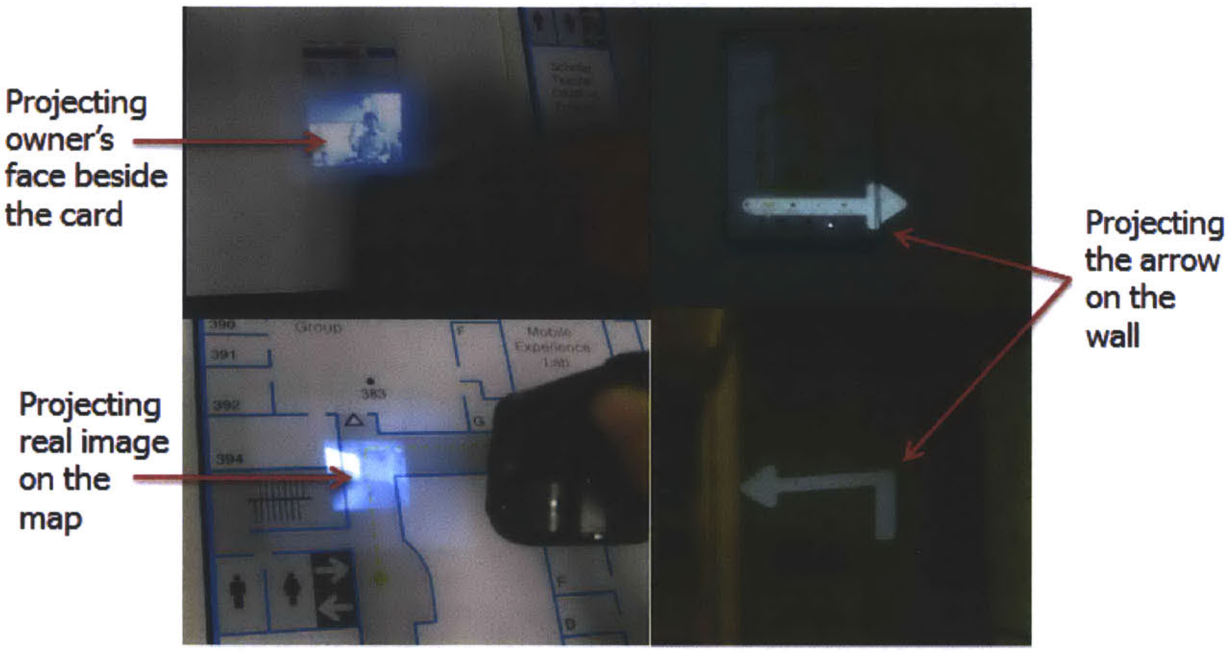


Figure 3.1. Handheld projector attached with webcam and sensors.

Our approach complements traditional abstract maps with actual environmental images and videos that help connect these abstract representations with the real world. In addition, users can get simplified directions while navigating by pointing Guiding Light at the floors or walls.

B. Characteristics and the design of user interface for handheld projector based AR

The core metaphor involved in the design is that of a flashlight, which reveals objects in and information about the space it illuminates. The users only need to point the device on the walls or floors to get augmented information through the hand-held projector. In contrast to existing heads-up displays that push information into the user's field of view, Guiding Light works on a pull principle, relying entirely on users' requests for and control of information.

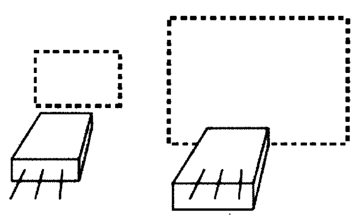
While screen-based AR in handheld devices requires users to divert visual attention to small screens, Guiding Light users can keep their eyes on an object of interest or a pathway. Users can control what information is to be projected by changing the angle and distance between the projector and an object. Tilting, panning, and zooming also change the information that is displayed (Karl et al. 2010).

We can classify projection spaces into two types, 1) objects, the outer surfaces of which become spaces for projection, and 2) spaces such as walls, floors, and ceilings that surround the objects. The surroundings (i.e., walls) become spaces for projection. The two projection space types require different projection strategies and methods, which will be described in the following.

1) Design consideration for objects

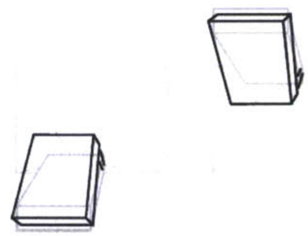
Maps or any objects inside a building can be embedded with more than one piece of information, and these pieces can be complex enough to form layers and lists. With handheld projectors with AR, we can design a user interface using a projection strategy such that users can filter and access embedded information as they desire. We have identified three types of projection strategies using gestures such as moving arms or turning wrists. Although gestures can accommodate more complex movement patterns, the following can be considered basic elements of projection strategies that can be implemented by handheld projection-based AR.

i) Projected distance from a target object:



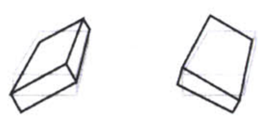
The distance between the projected object and the projector directly influences the size of the projection. This effect can be directly mapped into localizing a boundary of interests. Also, it can be used as a method to zoom in and out to access a layer of embedded information inside the object. For instance, when the device approaches a target object closely, more detailed information can be augmented on the object. Conversely, when the device is far away from an object and information is projected from afar, only simplified or abstracted information can be augmented on the object.

ii) Projected direction from the target object:



The projection direction angles, for example, projecting from above to the ground, can be interpreted as the user's perspective observing the object. The perspective angles can be mapped to filter the information content. For instance, when a poster that contains a car that is represented in 3D on a 2D surface, a user can augment information from the top down angle. The angular difference in projection can be translated into user's intention that he/she may be interested in the roof of the car, and the system can filter other information and show more details related to the roof.

iii) Projected angle (or rotation) on the targeted object:



Rotation of the device by turning the wrist left or right while projecting can be mapped into an interface for navigating a list of information. For instance, long lines of words or a long list of images may not be presented in the limited projected space; turning wrist left or right can be used as an interface to scroll up and down, or left to right to navigate the list of content.

A USER SCENARIO USING GESTURES

A user stands in front of a picture and flashes the projector on the picture. General information like history, the artist, and a description flows out with sound and annotation. This description is more interactive than the static description panel beside the picture - annotations can be directly augmented on the picture so instead of "at upper left side above the waterfall..." just "here" is enough with highlighting.

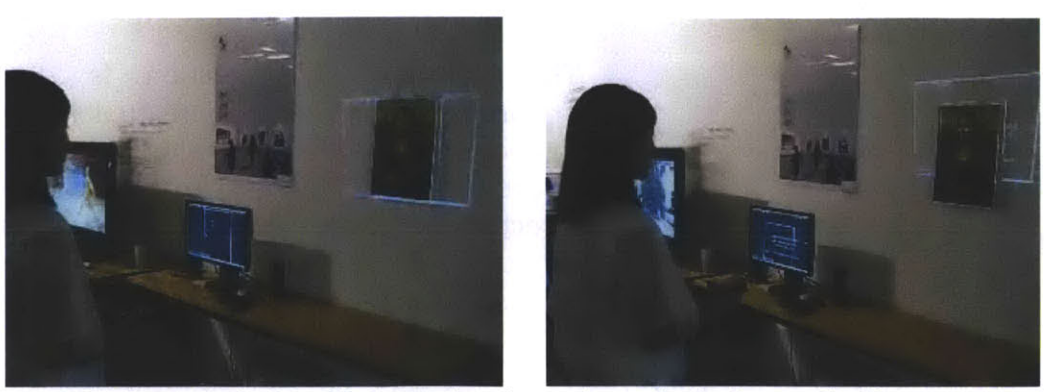


Figure 3.2. The granularity of information depends on flashed area. (Left) Larger portion with general information (Right) Smaller portion with detailed information

When the user is interested in and wants more detailed information, he/she flicks up once to cycle to the next mode and several points are highlighted. He/she steps closer and flashes on a part he/she is interested in, and a more detailed description flows out. These detailed descriptions are stored in the server, so they can be easily updated. The user flicks up once more to access the user-created content mode. Annotations, drawings and comments from other users are displayed.

Example User Interface

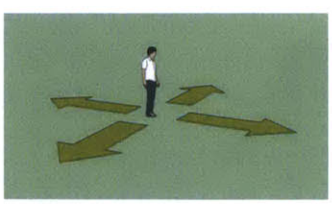
The system uses the concept of a flashlight, hence the first interaction that happens between the user and the device is "Turn on the Guiding Light and flash something." As the user flashes on an object, the device automatically identifies the flashed object and retrieves information from the server. The granularity of information depends on the position and the portion of object that is being flashed on. Generally, flashing on the entire object will bring coarse and general information, and flashing on a small detail will bring more detailed and fine-grained information.

It also supports navigational interaction. By flicking the entire device up and down, the facet of information will be changed. For example, the default information displayed is the historical explanation about the picture. After flicking up once, several spots are highlighted to indicate important checkpoints. The next flick brings comments from other visitors. Tilting the device left or right will scroll the screen up and down.

2) Design consideration for surrounding spaces

The following four user interface considerations need to be taken into account for projecting information into spaces around objects, such as walls and floors using hand-held projectors.

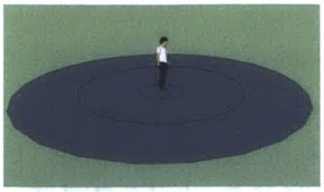
i) The direction of projection:



The direction of projection is the most important fundamental contextual information to decide how information should be presented in order to guide the user to move in the right direction. The designer needs to consider a strategy for displaying different types of information. Electronic compasses can be used to detect the direction.

ii) The distance of projection:

A comfortable average projection distance from users is approximately



1.7 meters. When a user approaches an end of a straight path (or an intersection), the user may want to project further (more than 1.7 m) ahead to investigate future directions. Therefore, we need to consider the strategy for what and how the information should be presented depending on the location of projected area. Calculating the location of projected area requires both proximity and tilt sensors not only to measure the distance of projected area from the device, but also to discriminate projection surfaces, wall vs. floor. Tilt sensors are used to support the proximity sensors by measuring the projection angle from the user' hand.

iii) Projection space:

Indoor spaces consist of basic elements such as floors, walls, ceiling, doors (entrances) and stairs. In our initial prototype of Guiding Light, guiding information was primarily displayed on the floor, and supplementary information such as a map was displayed on the walls. To expand the navigation directions to cover the entire building structure, designers may consider different types of projection surfaces.

iv) Projection target - point of interest vs. path (local vs. global goals):

Projections can be placed on any type of surface. The targeted area can be a surface which is a part of the navigation space, or an object, i.e. a map or a poster. Although the guiding information projected on surrounding surfaces should be designed for coherently pointing to the destination, augmented information on an object can be independent from path information. Therefore, it is important for the system to discriminate between global and local information projection spaces. This problem is challenging because the system may need to read the intention of the user.

A USER SCENARIO FOR NAVIGATION

The usage scenario is segmented into three interaction parts: a) determining a destination b) interaction with a map and c) guidance while navigating inside a building.

(a) Determining a destination

As a user enters a building, he or she can use, for instance, a business card as a token to let the system identify the desired destination. After the system recognizes the destination specified by the business card, the system presents a movie clip showing a picture of the person on the business card as well as a fast-forwarded path to the destination on a nearby wall or on the floor to provide an overview of a route to the target, as seen in the left image of Figure 3.4.

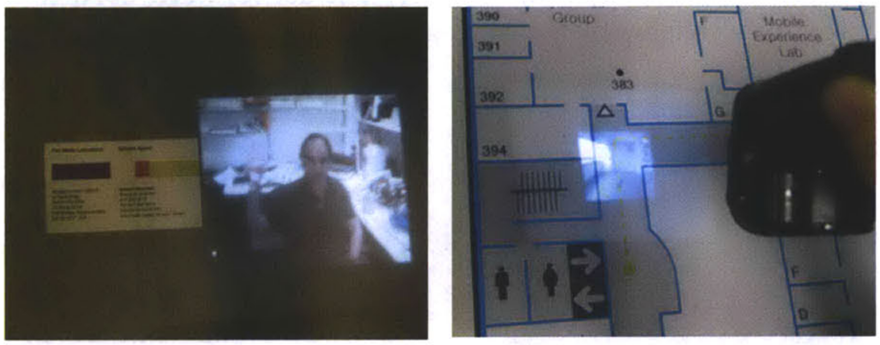


Figure 3.4. Examples of interacting with a business card and a map

(b) Interaction with map

When the user encounters a map in the building while navigating indoors, the user can get detailed information about the path by pointing the device to areas of interest. Then, the system projects an arrow to present a route to the destination, and it also augments actual images of scenes along the path on the map, especially on the decision-making points such as intersections, as seen in the right image of Figure 3.4. Through this interaction, the user can get familiar with unknown environments in advance so that when the user is en route, he or she can increase the confidence of being on the right path.

(c) Guidance while navigating inside a building

On arriving at decision-making points like corridor intersections, the user can get directions by pointing the Guiding Light onto nearby walls and the floor (see the left image in Figure 3.5).

Figure 3.5. Examples of using projected AR for navigation.

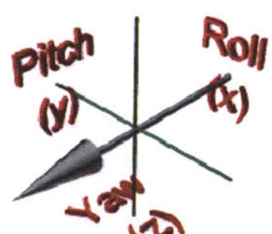
The user can point at any four directions - forward, backward, left and right on the path to get the guidance information in the form of arrows indicating the path leading to the destination. When the user approaches closer to the destination, the system provides information to help further clear up ambiguity by augmenting the office owner's information when the user points the device to the office doors as seen in the right image of Figure 3.5.

3.3 Implementation of Guiding Light

We had iterations of developing Guiding Light to test the use case sensors with pico-projectors for indoor and information navigation scenarios.

3.3.1 *Version 1*

The earliest version (Spring 2009) of Guiding Light was designed with a magnetic sensor[1] (orientation), an IR sensor (location) and a proximity sensor which were attached on a pico-projector[2] connected to a Nokia N95 phone. The magnetic sensor was embedded with a tilt compensate algorithm which provides 3 axes of rotation on the x, y and z plane. The sensor allows us to track the orientation of the attached projector in a user's hand. Although the positioning capability with the prototype was limited, the device was designed to explore the projection strategy based on the readings of the tilt sensor. Projected images and information are fed from the Nokia phone that is connected to pico-projector via A/V cable. The stream of the sensors is sent to the Nokia phone via Bluetooth to render the image based on the data that captures user's location (IR sensor), facing direction (yaw), projected distance (pitch), wrist turning gestures (roll) and projected on wall (pitch + proximity



1 HMC 6583? With tilt sensor providing pitch and roll.

2 What pico projector was it?

sensor). We developed the rendering process in J2ME running on the Nokia phone to provide arrow image, and it also handles simple route planning and navigation assistance.

Strengths:

i) Light weight sized computation processing was possible because of the use of orientation sensor.

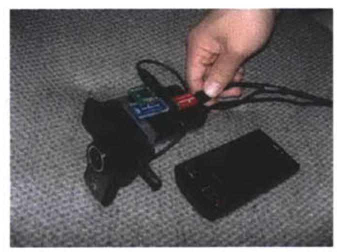
ii) It created effective experience of projected based augmented reality in the context of navigation assistance.

Weaknesses:

i) Positioning system in this version was very weak. It could handle only within 3 square meters and it was not large enough to fully explore the possibility of using the interface.

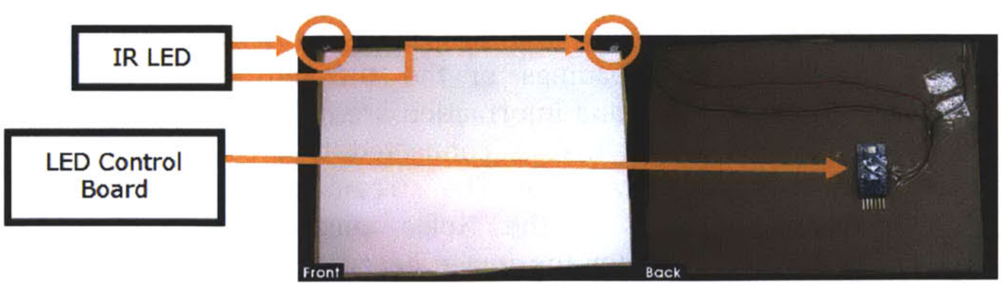
ii) It lacks the building scale route planning system.

3.3.2 Version 2



We extended our first prototype with a video camera that can detect multiple IR beacons to track projected distance and orientation from an investigated object. This version (Fall 2009) of Guiding Light was designed to interact with a poster-like object surface. By attaching IR LED beacons on the corners of a poster, and through a video camera with an IR filter, it can track the location of the surface.

By carefully aligning the projector with an attached camera, it can augment information on top of the desired location on the surface. We also added more hand gestures (distance from the object, and flicking up and down) that can be mapped to switch modes or navigate information space (the details are already covered in the Guiding Light Chapter).



Strengths:

i) Precise location detection of object surface allows better implementation of AR

ii) Richer interactivity with an object

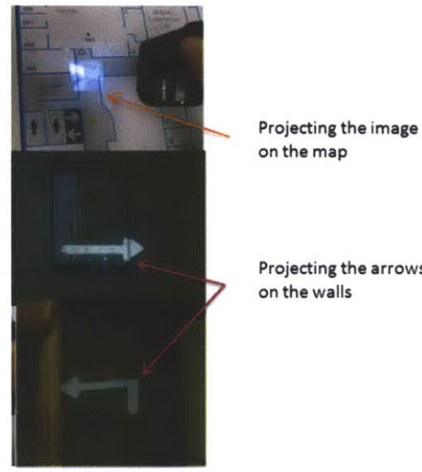
iii) Simple black/white blob detection requires little computation resource comparing to full computer vision approach. It can be run in real-time on a smart phone processor.

Weaknesses:

i) Requires expensive specialized tag such as IR LED beacons.

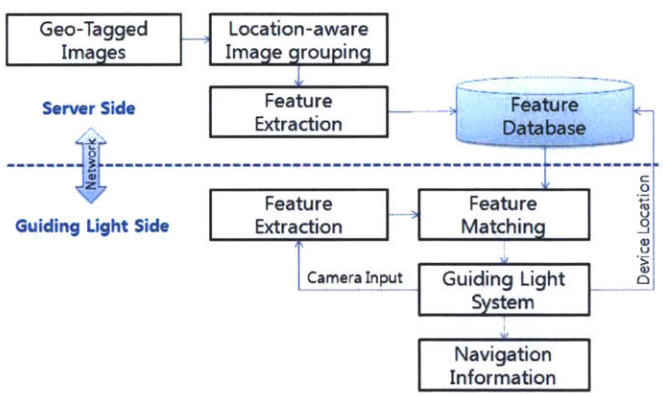
ii) Requires more computation power than the version solely depending on tilt sensors.

3.3.3 *Version 3*



We further investigated the design of the system with the primary use of computer vision for interacting with objects and for indoor navigation. In this version, we solely depend on a camera attached to a pico-projector. This implementation required bigger processing power than in phones, and we used a laptop as a center of the Guiding Light system. Both a camera and a pico-projector were connected to a laptop computer (Core Duo, 1.6 GHz, 2 GB ram). The system requires two set of tasks, recognizing images such as business cards and a map, and recognizing scenes of our surroundings. The former is required to identify the destination of the target location using the business card as a token and to interact with map when a user encounters a particular map. The latter is required for navigation assistance.

This version of system consists of two parts; the client (Guiding Light) and the server sides.



In client, we take an image from the camera of Guiding Light, extract features, run RANSAC to make sure individually matched features are consistent with other matches, and finally display the navigational information of the top-ranked image. The server side requires preprocessing for constructing a database of POIs (points of interest) in the building. The preparation of the database requires geographically tagged images of POIs like scenery near the decision-making points, office doors, and maps on the walls. Using the geo-tagged information, the system clusters POI images of the target area by confirming the user's currently predicted location through input from the camera.

For image recognition, used a widely adopted algorithm, SIFT (Scale Invariant Feature Transform) (Karlsson 2005), to extract features for the image matching process. When an image is acquired by the user by holding and pointing the device to the target area, the system confirms the position of the user and sends this geo info and the extracted features to the server. The server caches the geo-tagged key points, set E, in the user's current block. Given a SIFT key-points set E, and a target key-point vector d, then a nearest neighbor of d, d′ is defined as:

$$\forall d'' \in E, |d \leftrightarrow d'| \leq |d \leftrightarrow d''|, |d \leftrightarrow d'| = \sqrt{\sum_{i=1}^{k} (|d_i \leftrightarrow d_i'|)^2} \quad (1)$$

where, d_i is the i-th component of d. We implement the SIFT key-points matching algorithm which is based on nearest neighbor search algorithm in a KD-tree.

We have examined the system by detecting scenes on a long corridor (50 m) with 25 images, a 12 business cards and a map with 16 different parts. The recognition rate of the target images are required in three usage scenarios; A) recognition of business cards, B) recognition of a map for preview, and C) recognition of surroundings of the decision-making points that are required to give right directions to the user.

TABLE I
Recognition Accuracy

TARGET	ACCURACY
Business card	**82%**
Map for preview	91%
Surroundings of decision making points	93%

Table I shows the recognition results using the system. This shows that our system can be applicable in real indoor navigation situations.

Strengths:

i) Seamless interactivity across the object and the surrounding.

ii) Does not require any special active tag for recognizing an object or a scene from the surrounding.

iii) Simple and intuitive interaction required. Point and get augmented information for both input (determining a destination) and navigation.

Weaknesses:

i) Degrades the experience of mobility – requires carrying a laptop.
ii) Require sophisticated algorithm to use natural visual tags.
iii) Scalability issues:
    a. Difficult to extend image DB because of feature size of an image that requires lot of memory space.
    b. As the DB gets bigger, it requires more computation power to search for matching image.
iv) Sensitivity to the change of light and visual layout.
v) Hard to use in indoor environment where simple or repeating visual features that are common in office building environment.
    a. Quality of image recognition rate and identify-ability correlates to the complexity and diversity of natural image tags.

3.4 Current version of Guiding Light

From our experience of developing different versions of Guiding Light, our final design decision was in favor of using a sensor-based system over vision. A vision-based Guiding Light provides great potential, but as the processors in mobile devices get faster, the amount of data that covers a building is too big to fit in a phone. An alternative approach to solving this problem is to send a stream of image data to a server, or to cloud that can compute the image-matching algorithm in server. However, image data needs to be in high quality, and it requires having reliable and wide bandwidth to support such scenarios.

Our approach using sensors would lose delicate interactivity with objects, but it will handle its primary task: guiding pedestrians to a destination. This method may require less data transmission between server and Guiding Light. In addition, the sensors used in the device are already present in smart phones, such as e-compass, accelerometer, and gyroscope sensor, so we don't need to implement any sensors on top of existing phone. The detailed description of whole system is described in Chapter 5.

4 The Indoor Positioning System

In order to provide accurate guidance, navigation systems require accurate measurements for user position and orientation. There are a number of successful strategies for outdoor navigation, like GPS, but indoor navigation must necessarily use different sensing techniques. Indoor localization has relied on other infrastructures (Liu et al. 2007, Bruno 2003) like wireless access points and Bluetooth beacons. Guiding Light that implements user interface of projector based AR requires a positioning system that delivers both accurate location as well as direction; otherwise the information projected onto a floor or on a wall may cause confusion due to improper mapping of the real and augmented views.

With using magnetic sensors for direction determination, we have observed that the electronic compasses behave erratically inside buildings because steel and concrete skeletons distort the geomagnetic field: the compass doesn't point to the correct direction – our data shows an average of 45° error from the ground truth direction, and this error varies with location. As we mapped the distortions in order to calibrate our e-compasses, we noticed that the distortions are distinct to their collected locations. By using these distortions as map features, we can localize the user. In this chapter, we explore this idea to develop a novel indoor positioning system that uses this distortion as a feature that is a reference to a location.

The scope of this work covers i) results of identifying the characteristics of magnetic field signature as reference fingerprints to locations, ii) the performance of the positioning system using only magnetic fingerprint matching, and iii) a simple method for reducing outliers and rejected bad samples.

In the thesis we will present our system in two design phases; i) the initial system design for investigating the characteristics of the indoor magnetic field and ii) the system design for a pedestrian navigation system. In the pedestrian system design, we further present results of the system evaluation in different indoor environments to provide insights about the performance of using our fingerprint method. Lastly, we will present an experiment testing the stability of a building's influence on measurements of the earth's magnetic field and its relationship with our system's performance.

Our system to explore this development consists of a server that contains a magnetic fingerprint map and a client device that measures the magnetic signature of its current location. When the client collects the signature, it sends the data to the server for localization. The server compares the measurement with all the fingerprints stored in its map and reports back the position associated with the closest matching fingerprint. The server and client communicate via HTTP or via serial port when connected by mini USB.

Two separate processes, mapping and tracking, are required in order to infer a location, but the same device can be used for both. Our device design changed over the course of this project as we learned more about the problem. The initial device has been designed to capture the magnetic signature with maximum accuracy, while the later design is designed for mobility and faster measurement. Detailed description will be provided in the later sections.

4.1 The observed characteristics of indoor magnetic field

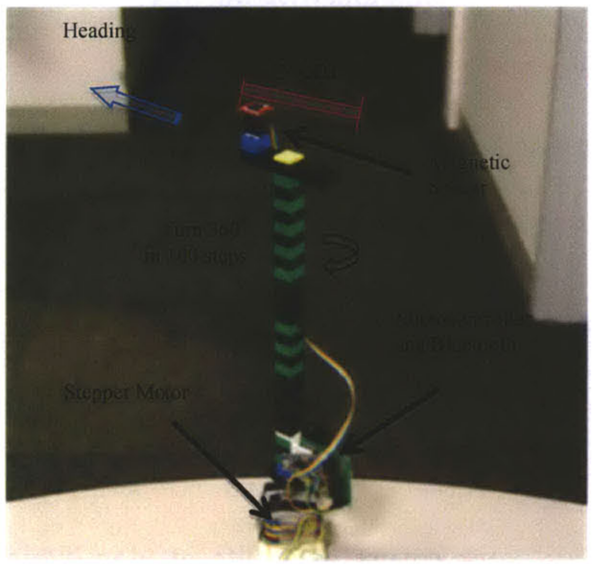
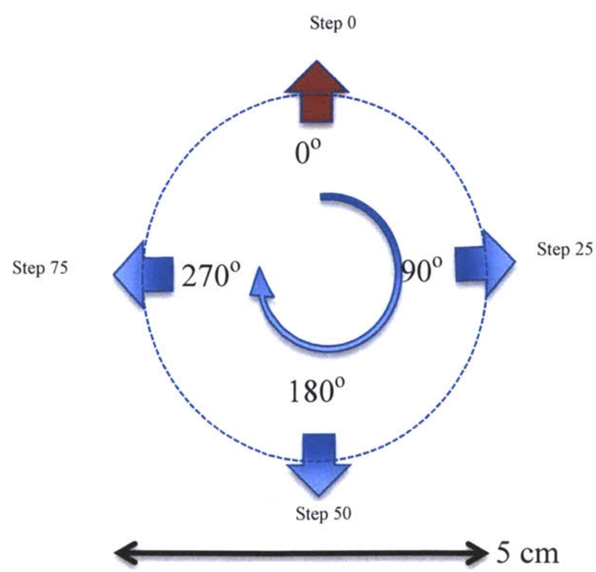
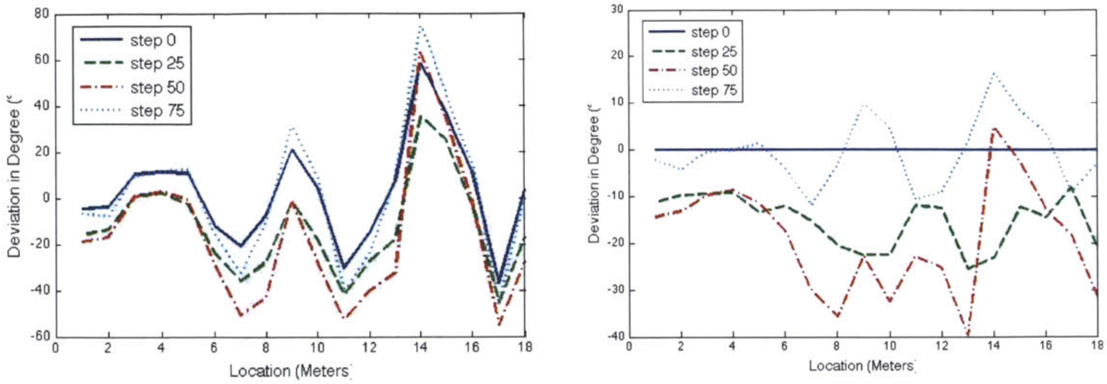


Figure 4.1. Initial design of the client device for detecting magnetic signatures



a. A figure of rotating sensor around a circle in 100 steps. Step 0, 25, 50, 75 are 90º apart.



b. Four heading directions measured at four steps. ***c. Bias controlled with step 0.***

Figure 4.2. Distortion of magnetic field measured in a corridor inside a building. The y-axis indicates the deviation error from true direction, and the x-axis indicates location along the corridor.

Our initial investigation started with measuring the magnetic field inside a building along a ~ 25 meter corridor every 60 centimeters from a height of 1 meter. Our device is shown in Figure 4.1. The purpose of the system is to map magnetic field distortion.

We used an electronic compass (HMC6343[3] - 3 axes magnetic sensor with internal tilt compensated algorithm) to measure the heading of the sensor. While measuring the heading, we used a stepper motor to rotate the sensor in a 5 cm diameter circle with 100 steps per rotation. We compared the measured heading with the actual heading.

As seen in Figure 4.2b, the deviation in heading varies significantly with position along the corridor. We suspect that the deviation errors correlate with the nearby building structure. It is important to notice that the variations between the four directions are also not equal. This means that the deviations occur on both large and small scales, otherwise we should see the fluctuating parallel lines. Figure 4.2.c amplifies the independent variation from other varying lines by subtracting the value of Step 0.

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[3] Datasheet of HMC 6343 - http://www.magneticsensors.com/datasheets/HMC6343.pdf

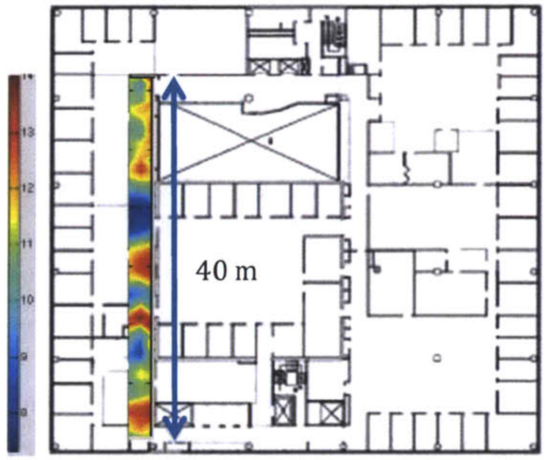


Figure 4.3. A magnitude map (in unit of μT) of the magnetic field inside the experiment area is shown in the left side of the figure.

4.2 Initial investigation for the system design

To investigate the feasibility of using the fingerprints corresponding to positions, we built a system to collect two datasets: one for creating the magnetic field fingerprint map, and the other for testing the localization performance. The goal of the investigation is to measure the sensitivity of the magnetic signature to determine the resolution of the fingerprint corresponding to accuracy of the system.

The measurement was conducted in a lab building (shown in Figure 4.3) that houses machine shops, machine rooms for servers, and desktop computers – very similar to settings in a computer science lab. The framework of the building consists of steel and concrete. For fingerprint mapping, as we continue to use the same method we collected data every 60 cm along the corridor above 1 m from the floor around 5 cm diameter circle every 3.6 degrees parallel to the floor. In this measurement, magnetic field $\boldsymbol{B}$ was measured with a three-dimensional vector $\boldsymbol{m} = \{m_x\ m_y\ m_z\}$ produced from the HMC6343. Locations and directions are indexed on each collected data such that data can be identified with the indices. $\boldsymbol{E}_{L,K} = \{\boldsymbol{m}_{0,1} \ldots \boldsymbol{m}_{0,99} \ldots \boldsymbol{m}_{59,0} \ldots \boldsymbol{m}_{59,99}\}$ where L is the index for location along the corridor and K is the index for direction. We have collected a total of $60_{\text{location points}} \times 100_{\text{directions}} = 6{,}000$ data features.

4.2.1 Algorithm

Our primary method for finding location is based on calculating least root mean square (RMS) difference between each location point d in the test dataset and the map dataset E. The following expression also accommodates the principal method we used with finding the nearest neighbor; given a map dataset E and target location fingerprint d, then a nearest neighbor of d, d' is defined as:

Equation 1

$$\forall d'' \in E, |d \leftrightarrow d'| \leq |d \leftrightarrow d''|, |d \leftrightarrow d'| = \sqrt{\sum_{i=1}^{k}(d_i \leftrightarrow d'_i)^2}$$

where d_i is the i_{th} feature component (i.e., ***m***) of d. Then, the difference between the location index (ground truth) of test dataset and the index of nearest neighbor d' in the map dataset E are used to estimate the accuracy of this method.

We computed the RMS differences with 8 different combinations of ***m*** in d where $d^k = \{\mathbf{m_1}\ldots\mathbf{m_k}\}$ with common denominator k = {100, 50, 25, 20, 10, 5, 4, 2} satisfy that the distance between indices of the feature component is equal. For example, an instance of d^5 can be $\{m_1, m_{21}, m_{41}, m_{61}, m_{81}\}$ or $\{m_2, m_{22}, m_{42}, m_{62}, m_{82}\}$, where the degree difference between indices is 72°. In our analysis, we computed all combinations in the map dataset corresponding to d^k in order to find the correlation between the number of features and accuracy. The purpose of this analysis is to estimate the most cost effective number of sensors that can be placed in a circumference, which has been emulated by a stepper motor collecting data around the circle.

4.2.2 Initial Findings

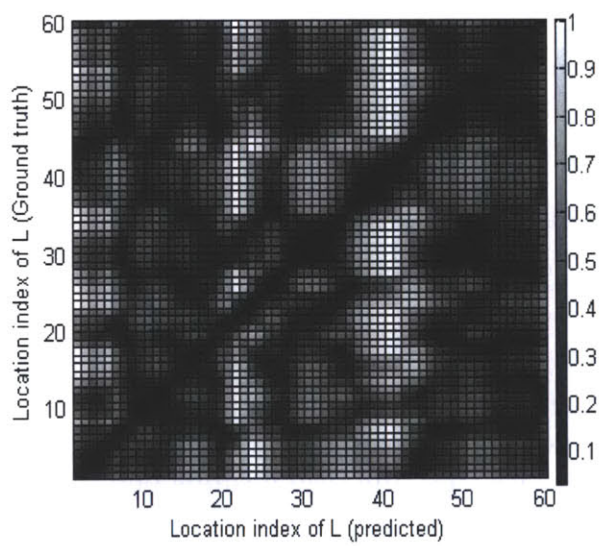


Figure 4.4. Normalized confusion matrix of RMS error with k=4. The x- and y-axes indicate the ground truth and predicted locations respectively.

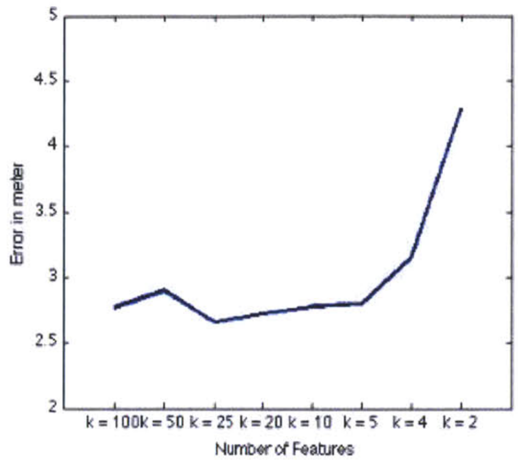


Figure 4.5. Results of mean errors produced from a function of K - number of feature vectors used in a fingerprint.

4.2.3 Results

The confusion matrix of RMS errors between the map dataset and test data set using d^4, as shown in Figure 4.4, provides us an overview of how well the localization using magnetic fingerprint method would work. As seen in Figure 4.4, most of the lowest RMS differences are along the line where x and y match, but there are some outliers. In total, our method has an err_{mean} = 3.05 m, err_{sd} = 4.09 err_{max} = 15 m, and 70% of the predicted data had errors of less than 2 meters.

Figure 4.5 provides overall err_{mean} with varying d^k. With varying k, the most cost effective number of sensors is 5, as the slope of err_{mean} increases noticeably when it passes K = 5.

Since a magnetic reading depends on position and orientation, we can use our fingerprint map to predict the orientation as well. Using the fingerprint with lowest RMS to predict the heading, our result shows that predicted heading has a mean angle difference from the true heading of 4.017º (SD = 4.6º) as shown in Figure 4.6.

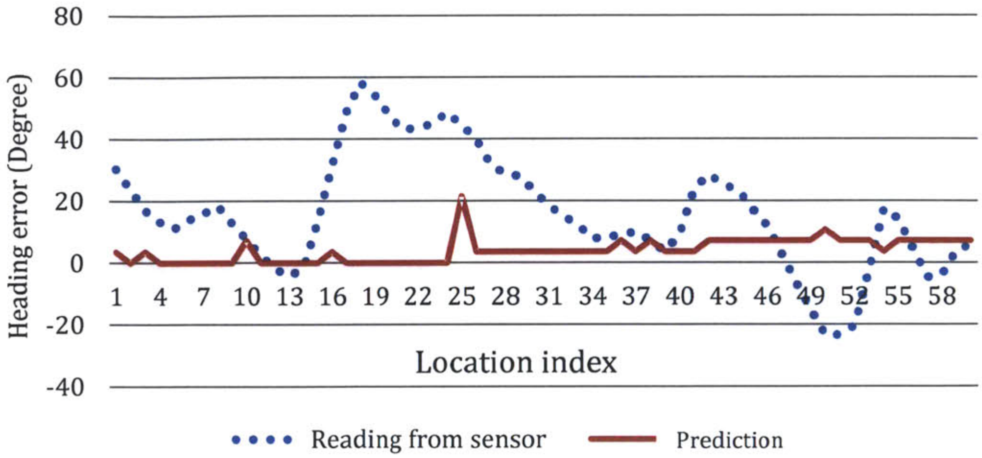


Figure 4.6. The blue graph plots raw heading directions directly extracted from the sensor reading. The red graph shows the predicted heading directions by the system. The x-axis represents locations along the corridor and the y-axes represents the heading error in terms of degree.

Encouraged by the promising results of this analysis, we built a more portable device that can perform localizations in real-time. In the next section we will provide an evaluation of this system and show the performance across several environments in the building.

4.3 System for pedestrian localization

With the new design, we've extended the map to include a larger area in two different buildings that are connected through two pathways. The goals of this design are i) to extend the system to provide a wearable device for humans, ii) to use the system on a larger scale, iii) to compare the performance within different structural environments, such as corridors and an atrium, and iv) to compare the fingerprint map between similar corridors in different floors.

4.3.1 System description

We have created a prototype with 4 sensors (Figure 4.7) of the same type used in the previous chapter, with ATmega328 based microcontroller (Arduino pro[4]) with communication capability via either Bluetooth or mini-USB cable with baud rate of 115200. The magnetic data, $\boldsymbol{m} = \{m_x, m_y, m_z\}$, are extracted from the 4 sensors via the I^2C protocol every 100ms. The size of $\boldsymbol{m}$ is 6 bytes, and the total size of a sample is 28 (24 + 4) bytes including two label indices, L and D, which are 2 bytes each. The collected data were sent to a laptop computer via a USB cable.

[4] Specification - http://arduino.cc/en/Main/ArduinoBoardPro

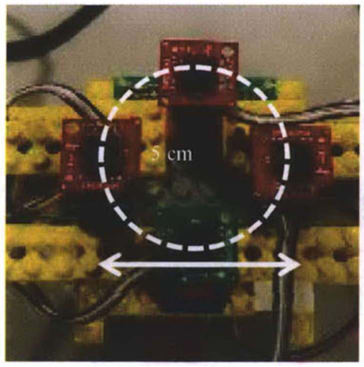
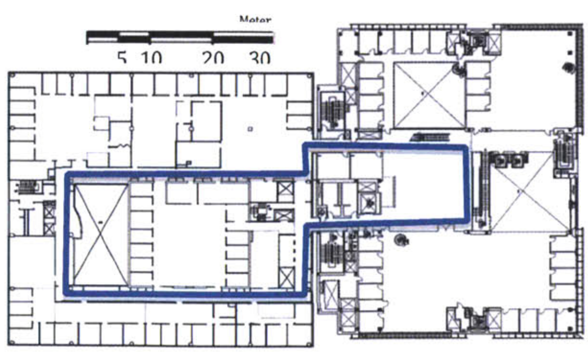


Figure 4.7. Wearable device for detecting fingerprints.

Unlike the previous device, this one is meant to be worn on the chest, so as to prevent arbitrary rotation. This changes the sensor to be in the vertical plane, instead of the horizontal plane like the last section. The magnetic field has similar variability in all three x, y and z axes (Figure 4.11 b, c, and d), so the sensor will behave similarly despite being in a different plane. To construct the fingerprint map, the sensor device was attached to the back of a chair; 4 feet above the ground near adult chest height. To support location recognition from any orientation, the chair is manually rotated 360 degrees with a 28 cm radius at roughly constant speed for 12 seconds to collect 120 magnetic fingerprint samples at each measured location (each location has 2.6k bytes of fingerprint data). The reason for rotating the chain is to collect a set of representative fingerprints in variety directions at each location. We are not predicting orientation in this particular test, so we do not need to accurately measure the orientation while mapping, and this saves considerable time The 35-meter corridor took about 12 minutes (ignoring movement time between locations) to collect a single trace of magnetic fingerprints. The test data were collected with the device attached to a person, sampling fingerprints in the place where the fingerprint map had been created.

Three areas were selected for measuring the performance of the system: 1) 187.2 m corridors shown in Figure 8.a, 2) 13.8 x 9.9 m^2 area in an approximately 20x20x15 m^3 atrium space shown in Figure 8.b, and 3) two corridors located at same locations on different floors shown in Figure 4.4.



a. Floor map shows a 187 m corridor loop

b. 15x20 m^2 atrium.

Figure 4.8. Mapping and testing sites in two connected buildings.

On the corridors in Figure 4.8.a, we collected fingerprints in the middle of the corridor in 60 cm steps to construct the map. We measured and marked the floor to capture this accurately, and we allowed people to walk through the area during measurement. The corridor is surrounded by a wall made of steel framed wooden panels and glass walls and is approximately 2 meters wide, on average. Similarly, we mapped the atrium on a 13.8 x 9.9 m^2 grid 60 cm apart on the floor. Inside of each cell in the grid, we collected fingerprints at 10 Hz sample rate, rotating the chair around with a period of 12 seconds to capture samples in all directions. On the grid (Figure 4.8.b) we have produced a map with a total of 40800 fingerprints = 979.2 K bytes.

The test data set was collected in a similar manner, sampling one fingerprint per step, a week later than the creation of the fingerprint map. We used floor plans to estimate the coordinates of the fingerprint locations. Both the map and test data were collected during day time.

We used a modified version of the RMS based nearest neighbor searching algorithm for localization that was used in the previous section. As we use 4 sensors for sampling fingerprints, the data structure of the system is changed such that d contains four 3 dimensional vectors, $\boldsymbol{d}_{\text{raw}} = [m_{x1}, m_{y1}, m_{z1}, m_{x2}, m_{y2}, m_{z2}, m_{x3}, m_{y3}, m_{z3}, m_{x4}, m_{y4}, m_{z4}]$. In addition, the data structure of the fingerprint map is defined as $\boldsymbol{E}_{L,K} = [\boldsymbol{d}_{1,1} \ldots \boldsymbol{d}_{1,k} \ldots \boldsymbol{d}_{L,1} \ldots \boldsymbol{d}_{L,k}]$ where L is the index for location along the corridor and K is the component ID collected at location L.

In addition to raw vectors, we also consider using the unit vector $\boldsymbol{u}$, and norm $\boldsymbol{n}$, defined as follows:

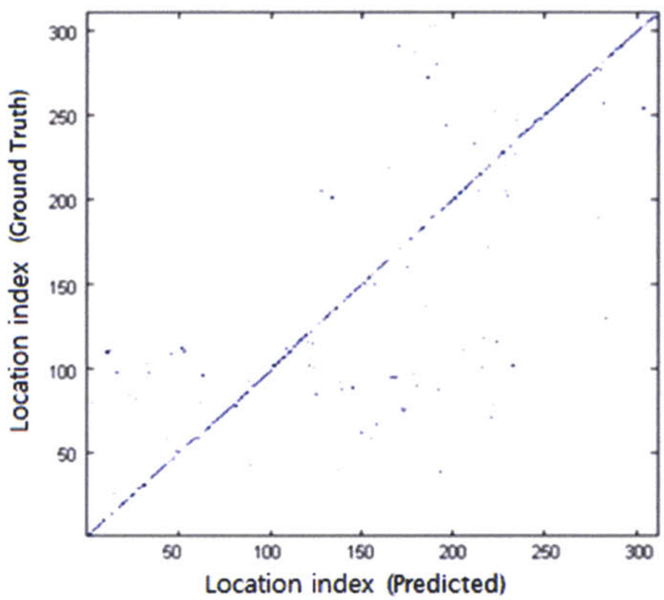
$\boldsymbol{d}_{\mathbf{norm}} = [n_1, n_2, n_3, n_4]$, where $\boldsymbol{n}_k = \sqrt{m_{xk}^2 + m_{yk}^2 + m_{zk}^2}$

$\boldsymbol{d}_{\mathbf{uint\_vector}} = [u_{x1}, u_{y1}, u_{z1}, u_{x2}, u_{y2}, u_{z2}, u_{x3}, u_{y3}, u_{z3}, u_{x4}, u_{y4}, u_{z4}]$, where $\mathbf{u}_{(x,y,z)} = m_{(x,y,z)k}/\boldsymbol{n}_k$,

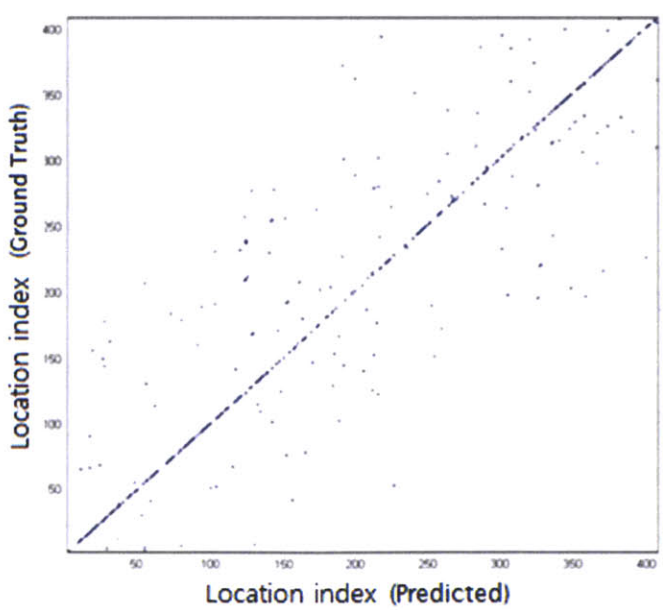
4.4 Evaluation

4.4.1 Results of performance in corridors and atrium

Figure 9 shows predicted verses actual point index for the corridor and atrium. Most of the points are correctly identified, however there are some outliers which cause a large mean error, $\hat{e}$, and a large standard deviation of $\hat{e}$. The atrium had slightly worse performance, but point index can be misleading since we measured in a grid: adjacent points in a grid won't necessarily have consecutive indices. To get a better sense of performance, we calculated error distances.



a. Least RMS errors in corridors



b. Least RMS errors in atrium

Figure 4.9. The graphs show the results of measuring performance of the system in terms of RMS error in the corridors (a) and the atrium (b). The x- and y-axes indicates Location indexes of ground truth position and predicted position respectively.

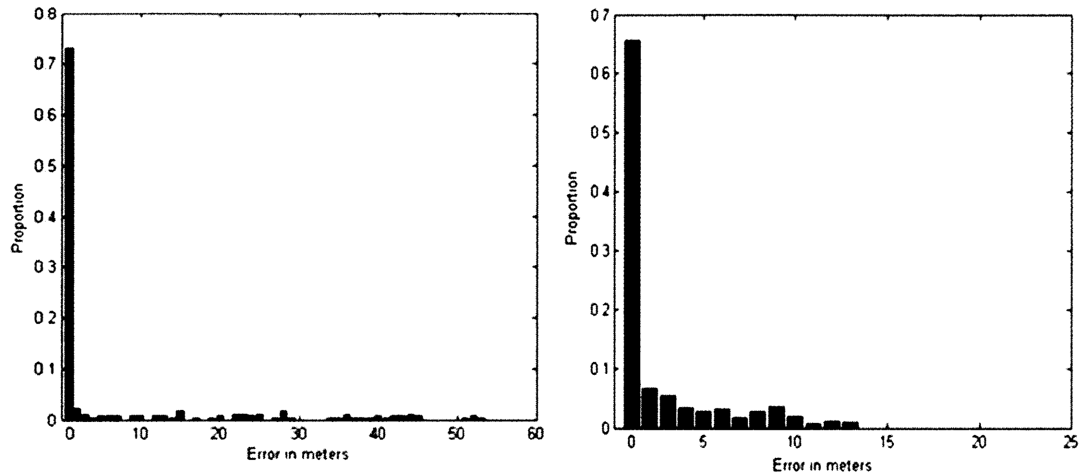
Table 4.1 summarizes the localization experiment with the nearest neighbor searching algorithm. The result is computed based on 310 test data points compared to 37200 fingerprints in the map data set for the corridor experiment; 408 test data points were compared to 40800 fingerprints for the atrium experiment.

The results of the experiments (applying no speed or moving direction constraints) using the entire search space are: err_{mean}= 6.28 m (err_{sd} = 12.80m, err_{max} = 52.60 m) for the corridor and err_{mean} = 2.84m (err_{sd} = 3.39 m, err_{max} = 12.82 m) for the atrium. The mean and deviation of the corridor is larger since the covered area is larger, encompassing 178 m of corridors in two buildings. The overall performance looks better in the atrium experiment as the $Err_{mean}$is small. However, the corridor experiment has more room to produce an outlier far (maximum 73 meters) from the true position whereas the maximum outlier the atrium can produce is small (15 meters).

The histogram (Figure 4.10) of error distribution for both experiments shows that 75.7 % of the predicted positions have an error less than 1m. In our result, Err_{mean} correlates linearly with the number of locations in the search space.

Search space in radius (m)	Searching amount in Map (%)	Err_{mean} (m)	Err_{SD} (m)	Err_{max} (m)	Failure rate (%)
Corridor experiment					
>72	100	6.28	12.80	52.60	0
40	78	4.50	9.89	39.82	0
30	56	2.81	6.82	28.55	0
20	32	1.25	3.63	19.45	0
10	12	0.48	1.43	9.91	0
5	6.2	0.26	0.62	4.96	0
Atrium experiment					
>15	100	2.84	3.39	12.83	0
9	82	2.24	2.91	8.99	0
6	50	1.36	1.75	5.80	0
3	17	0.64	0.85	2.99	0
1	1.9	0.18	0.29	0.80	0

Table 4.1. The result of localization performance in terms of Err between ground truth and predicted location



a. Corridor *b. Atrium*

Figure 4.10. Histogram of distance error.

Two general methods can be applied to reduce error: i) adding additional localization information via an external source and ii) applying constraint models in the algorithm such as simple parameter adjustment or building a model, i.e. particle filters (Gustafsson et al. 2002). For additional localization, Bluetooth beacons or 802.11 based positioning systems (3 – 30 meter accuracy range) with an update rate in the range of a few seconds (Hui et al. 2007) can be used to filter outliers. Accuracy ranging from 2.5 to 8 meters in corridors and 2 to 5 meters in open spaces is observed from our informal experiments using the 802.11 RSSI fingerprint method (Kaemarungsi 2004). The result of the experiment with varying limiting search space, shown in Table 1, provides a possibility for potential enhancement on localization performance with supporting localization assistant.

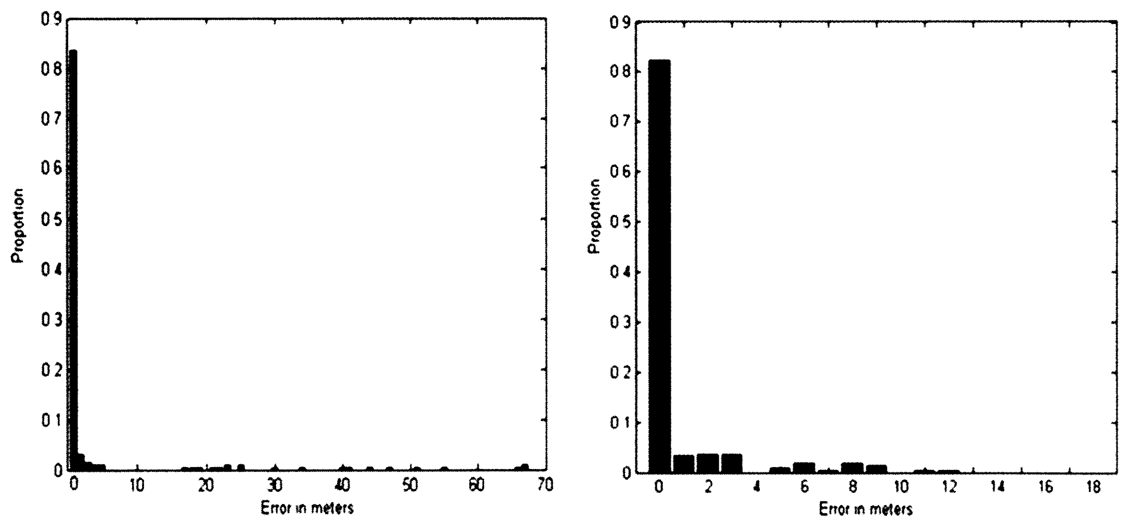
In our study, we applied constraints in our searching algorithm to reduce outliers. The table shows the result of applying constraints in our Nearest Neighbor algorithm by i) varying the search space from last known position and ii) filtering the predicted position by adding conditions in our algorithm. In addition to $\boldsymbol{d}_{raw}$, we compute using $\boldsymbol{d}_{\text{norm}}$ and $\boldsymbol{d}_{\text{unit\_vector}}$ to get estimated position. The location results produced by the three different vectors are compared, and if they are close, we accept the position. This is defined as: $|\boldsymbol{L}'_{\text{raw}} \leftrightarrow \boldsymbol{L}'_{\text{norm}}| \leq 1$ or $|\boldsymbol{L}'_{\text{raw}} \leftrightarrow \boldsymbol{L}'_{\text{unit vector}}| \leq 1$, where $\boldsymbol{L}'$ is a location index of $\boldsymbol{d}'$ as defined in Equation 1 in the previous section. To get an initial position, we used the strategy of expanding the search space to its maximum and then reducing it to the target search space size.

Search area in diameter (m)	Searching amount in Map (%)	Err $_{mean}$ (m)	Err $_{SD}$ (m)	Err $_{max}$ (m)	Failurerate(%)
Corridor experiment					

>72	100	4.96	13.94	70.59	24
40	78	1.65	6.15	45.72	43
30	56	0.66	3.22	27.18	44
20	32	0.32	1.15	28.77	40
10	12	2.74	7.01	9.918	28
5	6.2	0.23	0.56	4.96	4
Atrium experiment					
>15	100	0.96	2.17	11.32	57
9	82	0.61	1.75	9.69	73
6	50	1.63	3.07	12.30	78
3	17	2.65	3.77	12.40	78
1	1.9	6.75	4.30	15.19	62

Table 4.2. Result for the modified algorithm.

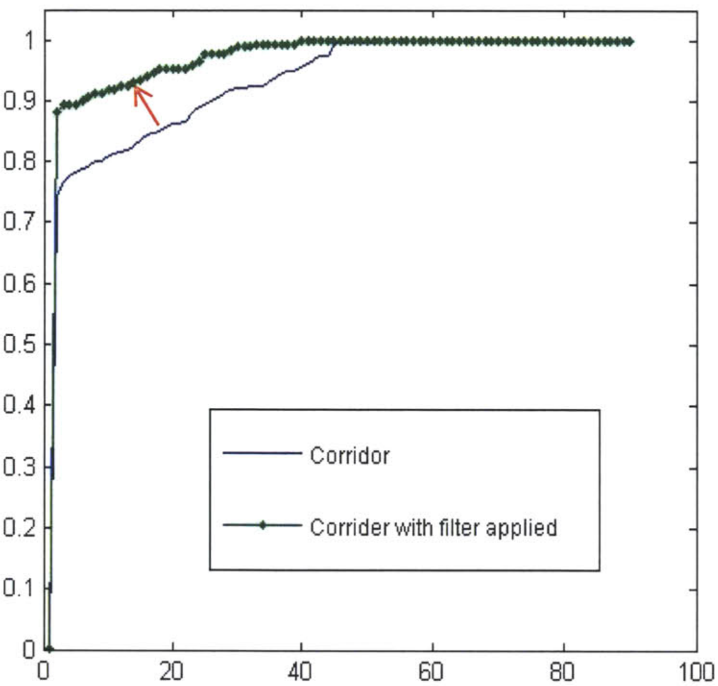
The result of overall performance of applying constraints is listed in Table 4.2. The algorithm effectively filtered the noise – 88 % of the predictions fall under 1 meter of error in the case of full search space in the corridor and 86.6% for the atrium.



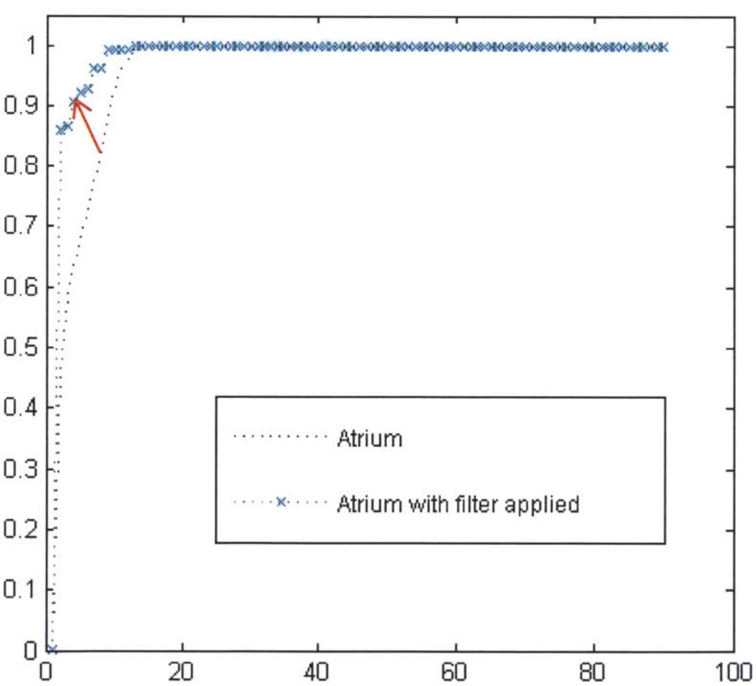
a. Corridor ***b. Atrium***

Figure 4.11. Reduction of error using filters shown in histogram of distance error.

Since this filter rejects inaccurate predictions caused by noisy measurements, multiple rejections can lower the update frequency. However, in our real-time tests, the device was able to produce updates faster than 1Hz. Using a search area constraint in our model can make it sensitive to noise, and more importantly, increases the likelihood of falling into the local minimum problem (Georgiou et al. 2010). However, a more advanced model (such as a particle filter) could avoid this issue, at the cost of more computation power.



a. Corridor CDF of distance error in meters

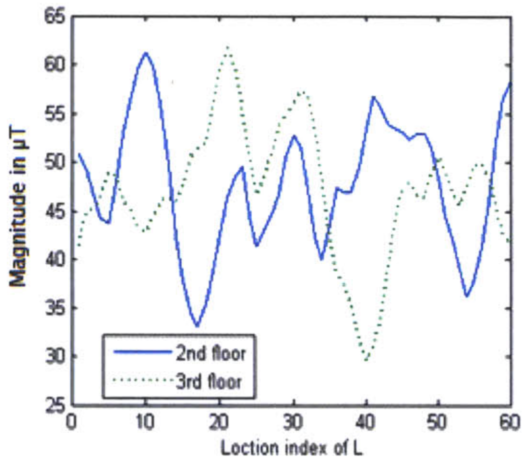


b. Atrium CDF of distance error in meters

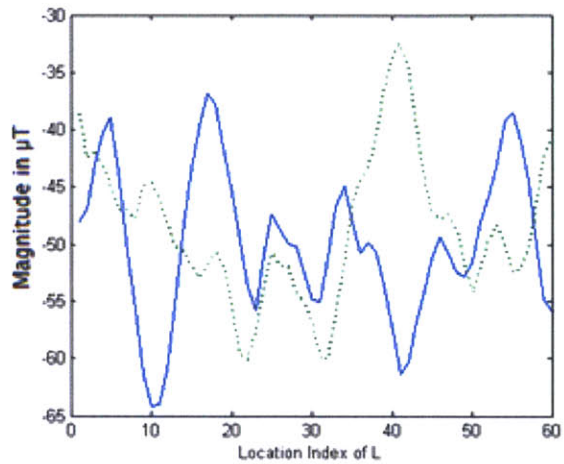
Figure 4.12. Cumulative distribution function of distance error produced by the system. The graphs compare the result of four results shown in Figure 4.10 and 4.11.

4.4.2 Results of comparing same locations of corridors in different

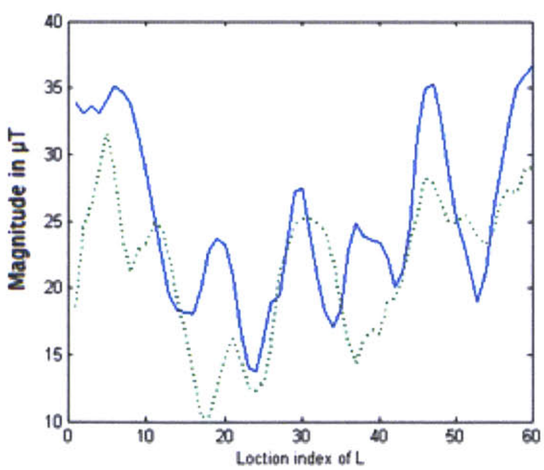
We have compared magnetic fingerprints across different floors at same locations, i.e., same corridors, because we speculate that the same location may have the same structural skeleton that may influence the magnetic field. The table shows the magnitude difference on each floor. Although the peaks of the varying magnitude of the magnetic field along the corridors show correlation, the magnitude of the field does not.



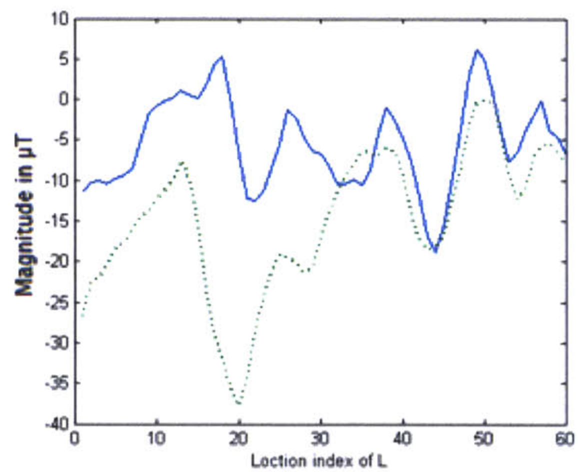
a. ||m||



b. m_x



c. m_y



d. m_z

Figure 4.13. The trace of measurement of a magnetic field on 2nd and 3rd floor.

We also examined the fingerprint difference between floors using a dataset with 120 location points, 60 points from each floor. We tested in the corridor shown in Figure 4.3 (and Figure 4.9.c) and the corridor directly underneath on the 2nd floor. The basic layout along the corridor is the same, but some parts of the walls along the corridor are glass.

The result of the experiment shows that no points were mistakenly predicted to be on the wrong floor.

	True location		
Predicted location		2nd Floor	3rd Floor
	2nd Floor	1.0	0
	3rd Floor	0	1.0

This result shows that the same locations on different floors may have different magnetic signatures. However, we cannot generalize this result as the size of the experiment is small and this may only be true in the building we tested.

4.5 Indoor magnetic field stability

The stability of geo magnetic field inside of a building is critical to determine the long-term performance of our system. Since the field can be affected by many different elements, we examined the 1) magnetic field stability inside a building over time, 2) the effect of moving objects on system performance, and 3) the effect of objects carried by the user.
To examine the field stability over time, we have collected three datasets of 60 fingerprints along a corridor. Each dataset is collected at the same location but at different times. The collected data are considered as a vector set, M_{init}, M_{2_week}, and M_{6_month}, where M_{init} and M_{2_week} were taken 2 weeks apart and M_{init} and M_{6_month} were taken 6 month apart. We examine the similarity between the sets in terms of angle differences (Equation 2) and magnitude differences (Equation 3) as defined as the following:

Equation 2.

$$CosineSimilarity\ (A, B) = \frac{1}{n}\sum_{i=1}^{n} \frac{(A_i \bullet B_i)}{||A_i||\ ||B_i||}\ \text{, where n = 60}$$

Equation 3.

$$Magnitude\ (A, B) = \frac{\sum_{i=1}^{n} ||A_i||}{\sum_{i=1}^{n} ||B_i||}\ \text{, where n = 60}$$

The result of our analysis shows that CosineSimilarity(M_{init}, M_{2_week}) = 0.9997, and CosineSimilarity(M_{init}, M_{6_month}) = 0.9977. For the similarity of the magnitude, it shows Magnitude(M_{6_month}, M_{init}) = 0.99 and Magnitude(M_{2_week}, M_{init}) = 1.01. This result, as shown in Figure 12, validates that the magnetic field did not change over 6 month period of time.

To examining the effects nearby moving objects, we tested several scenarios. First we measured the effect that a moving elevator might have on localization. We sampled without the elevator, and then tested with the elevator in place. We measured the RMS error as a function of distance from the elevator. We also tested the effect of smaller mobile objects by fixing the sensor location and measuring RMS error as the object is brought closer to the sensor. We measured the effect of a work-bench (Figure 4.13.a), a laptop (15" Macbook Pro 2008 model), a mobile phone (Samsung Galaxy S) and a wrist watch (Figure 4.13.b). Lastly, we tested the effect of furniture rearrangement in a room. We sampled the fingerprint with furniture in the room (Figure 4.13.c), and then took a second sample with furniture removed (Figure 4.13.d).

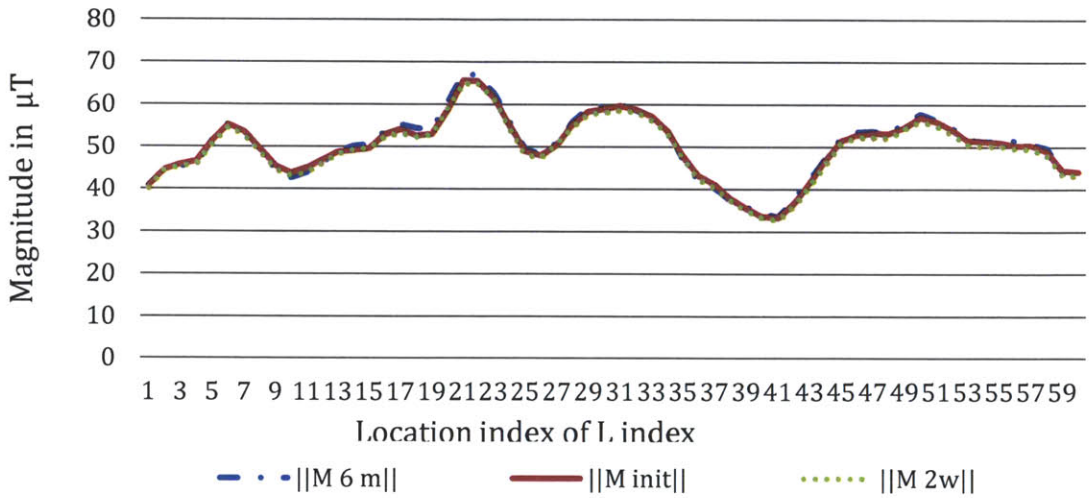


Figure 4.12. the graphs represents magnitude of magnetic fields $||M_{init}||$, $||M_{2\_week}||$ and $||M_{6\_month}||$. The x-axes represents the location index number, and the y-axes represents magnitude in μT.

RMS error does not directly convert to localization error, but we can compare the RMS errors caused by objects to RMS distances between fingerprints in the map. We find that the minimum RMS distance between any two measured points in our fingerprint map is 1.96 μT. In order for a measured location to still be resolved to the correct fingerprint, we assume that the RMS error caused by an object or other disturbance must be less than 0.98 μT. We consider this to be the error tolerance. In most cases, the presence or absence of objects introduced an RMS error of less than 1 μT when the objects were 12.5 cm distanced apart, as shown in Figure 4.14. The one exception was standing next to the elevator.

As shown in the Figure 4.13.b.2, the overall error drops quickly with distance from the sensor. In the case of elevator, the RMS error drops below 1 μT when the sensor is about 1.3 meter away from the elevator whereas a work bench full of metal tools and electronic devices didn't change the error very much. Similarly, error measured in a room with and without furniture also was not significant (RMS error = 0.71 μT).

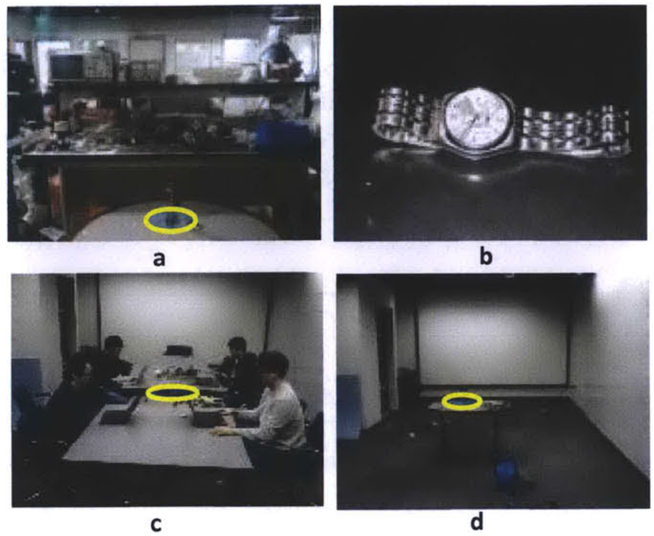
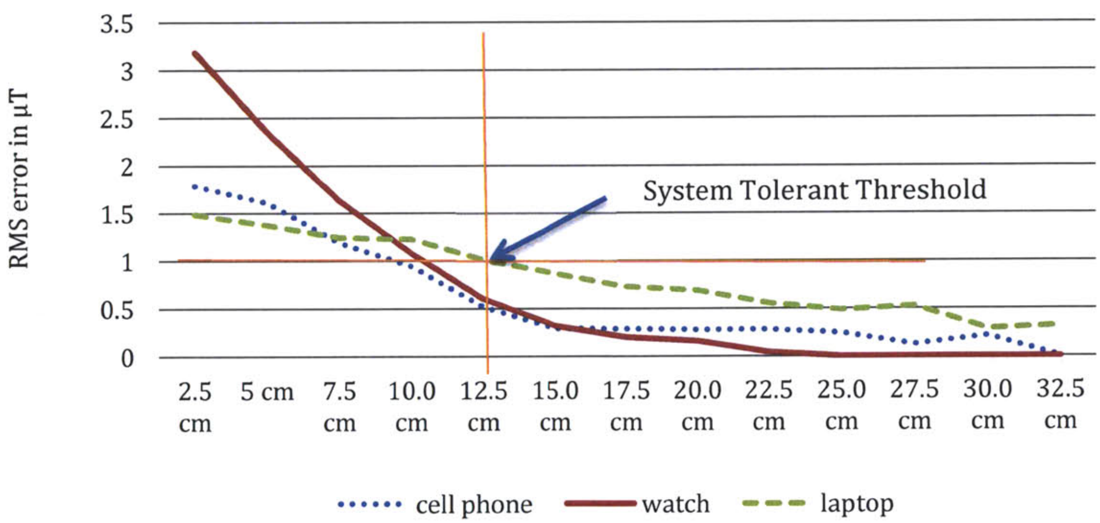


Figure 13. The picture shows the test settings for measuring magnetic field changes due to a work bench, a watch, electronic devices, and furniture. The yellow circle indicates the location of a magneto sensor.

In the case of inference from carried objects such as a laptop, a cell-phone and a wrist watch, we note that the influence from these objects drops quickly as the distance increases to around 12 cm. Assuming the user is wearing the sensor as a badge-like device on their chest, any objects in their hands or in a backpack would be a sufficient distance away and thus have negligible effect.



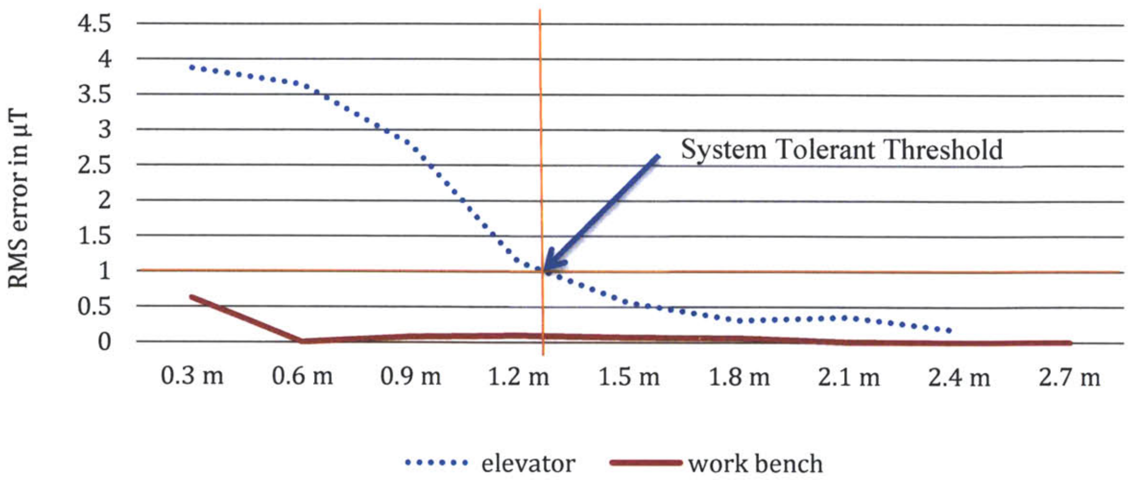


Figure 4.14. The graphs describe errors in our system caused by nearby metal objects. The y-axes represent the RMS error and the x-axes represent the distance between the object and the sensor.

4.6 Other observations

Besides the empirical results shown in the paper, successful tracking positions in different environments were observed from our informal experiments. One interesting observation we had is from an experiment conducted in elevators collecting magnetic field fingerprints inside the car at every floor and tracking the location as the car moves up and down, which shows 100% accurate prediction at each floor. The experiments were conducted in two different elevators in two different buildings (One in four story building, and another in a six story building).

This system was designed to work in a large building, but small scale positioning is also possible. Our informal result shows that within a 2x2x2 m^3 cubic area with 20 different locations in the fingerprint map, our system was able to differentiate locations separated by as little as 1.6cm. This example shows the potential to not only locate people in a building at the meter scale, but also at the centimeter scale, such as for tracking objects on a desktop. For future work we will investigate its usage for object tracking and tangible interfaces.

The results of the experiment show the most basic performance of the positioning system that is in the early design stage of the system. We provide an insight of how this system will work to support pedestrians with no constraints on moving and speed.

Compared to other positioning technologies listed in Table 4.3, our system performs reasonably well (precision of 90% within 1.64 meter accuracy) in positioning. Other systems have infrastructure overheads such as WiFi APs and beacons to broadcast signals inside buildings which contribute to additional costs associated with those systems. However, these systems have an advantage in terms of fixed local references provided by Wifi APs or beacons. Any false positives will not appear in a random location. Our system does not use any such local references and hence an outlier could be placed at any location not restricted to the area the device is currently working in.

System	Wireless Technology	Positioning Algorithm	Accuracy	Precision	Cost
Our system	Magnetic Fingerprints	Nearest Neighbor-hood with least RMS	4.7 m	90% within 1.64 m 50 % within 0.71 m	Medium
RADAR	WLAN RSS fingerprints	kNN, Viterbi-like algorithm	3-5 m	50% within 2.5 m 90% within 5.9 m	Low
Horus	WLAN RSS fingerprints	Probabilistic method	2 m	90% within 2.1 m	Low
Where Net	UHF TDOA	Least Square/RWGH	2-3 m	50% within 3m	Low
Ubisense	Uni-directional UWB TDOA + AOA	Least Square	15 cm	99% within 0.3m	High
GSM finger-printing	GSM cellular network (RSS)	Weighted kNN	5m	80% within 10m	Medium

Table 4.3. Wireless-based indoor positioning system by Liu et al. (2007) in the article of "Survey of Wireless Indoor Positioning Techniques and Systems.

Besides using our primary method of estimating position with NN based least RMS, outliers can be minimized by applying algorithms that model pedestrian movements, such as particle filter models. We also believe that by combining magnetic fingerprints with a WLAN RSS method (which can provide localization within 10 meters, according to Table 3), we can effectively eliminate outliers and achieve 0.45m accuracy.

For hardware design choices, we wanted to make a device that was roughly the size of a cell phone. We found that 5cm distance between sensors provided enough variability in magnetic field while still fitting our form factor requirement.

The limitation of the system is that the cost of mapping every space in a building may require significant effort and time using the presented method, and as the size of the fingerprint map increases the chance of error will increase.

5 System Description

This section describes the underneath architecture of indoor navigation assistance system and it's frontend, Guiding Light, that provide an user interface. In general, designing a navigation assistance system requires handling four separate processes of 1) knowing where users are 2) identifying where the destinations are 3) planning for routes between two locations, and 4) supporting information while users traveling the path. In our architecture, the system is divided to three different components, namely, Guiding Light, Route Planner, and Location Tracker, which all of that processes the requirement collaboratively when a navigation assistance service is requested.

The following shows the high level flow of a process that can be described with simple steps:

Step 1: Position update
Location Tracker constantly updates current position and direction of the user.
Involved System: Location Tracker (Hardware + Tracking Algorithm)

Step 2: Determine destination
User determines the destination through user input - typing the name of person to visit, or by selecting a predefined destination from a list.
Involved System: Guiding Light

Step 3: Route to destination
Route Planner gets the two points (start point, destination point) and computes a list of intermediate points that connect between the start and destination points. The route information is sent back to the frontend device (i.e. Guiding Light).
Involved System: Route Planner

Step 4: Guiding information
When the user points the device toward a floor, the device dynamically computes the direction of an arrow based on the current location and direction (from Step 1), and route from the backend server. The arrow corresponds to the immediate direction that user should follow through. When the user arrives at the destination, the system alerts the user that it is destination.
Involved System: Guiding Light and Location Tracker

The architecture of the system is designed to be modularized on each component such that it can be replaced by other existing components i.e., different types of positioning systems (GPS, or WiFi based indoor positioning system). As the communication between components is handled through network, i.e., UDP and TCP over IP network, each component can run in separate machines. This architecture can potentially support scalability such that it could dynamically change to a Route Planner and a Location Tracker that are implemented differently in other buildings.

In the chapter, we will describe the system of each component. Most of the components were emphasized on the software architecture. However, in addition to it for Guiding Light, we will describe the hardware constraints. Later in this chapter, we will discuss the advantages and disadvantages of our architecture and future works that can improve the system.

5.1 Guiding Light

In general, the fundamental role of a user interface for navigation assistance system is to provide an interface for the user i) to provide a current and desired destination to the system (input) and ii) to get guidance information from the system (output). The two minimum requirements are implemented differently depending on the choice of modality such as visual (text, map or pictures of landmarks), audio (utterance input output), or tactile (vibration).

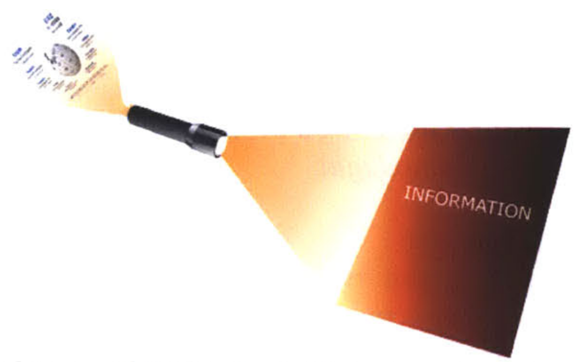


Figure 5.1 Conceptual image of Guiding Light that feed information from internet and present in-situ information on an investigated surface.

In the case of Guiding Light, it requires tracking the device's orientation that determines where the projected guidance is landed on a surface of surroundings. To explore our requirements, we have developed various versions of Guiding Light with different set of implementation as described in Chapter 3.

Current version of Guiding Light

From our experience of developing different versions of Guiding Light, our final design decision was in favor of using a sensor-based system over vision. Vision-based Guiding Light provides great potential, but as the processors in mobile gets faster, the amount of data that covers a building is too big to fit in a phone. An alternative approach to solving this problem is to send a stream of image data to a server, or to cloud that can compute the image-matching algorithm in server. However, image data needs to be in high quality, and it requires having reliable and wide bandwidth to support such scenarios.

Our approach using sensors would lose delicate interactivity with objects, but it will handle its primary task: guiding pedestrians to a destination. This method may require less of data transmission between server and Guiding Light. In addition, the sensors used in the device are already equipped in smart phones, such as e-compass, accelerometer, and gyroscope sensor, so we don't need to implement any sensors on top of existing phone.

5.1.1 Hardware Configuration

Our prototype is implemented with three hardware pieces: a pico-project, a mobile phone, and a Magnetic sensor badge for localization. The phone is the center of other hardware devices that organizes the data flow between the devices. Visual stream for displaying guidance information is fed from the phone to the pico-projector via AV cable, and the location badge is connected to phone via Bluetooth. Two pieces of orientation information, yaw and pitch, are used to track the projected angles. The pico-projector is required to be physically attached to the phone to use an embedded sensor to track the projectors tilt angle (projected angles from wall and ground), and the direction the user should be facing in order to get yaw.

5.1.2 Architecture of the Guiding Light

Guiding Light implements two main process layers: a) a layer with sub process that retrieves information from external components, and b) the other layer that renders augmented information for visual display as shown in the system block diagram. The layers are developed on Android platform on Samsung Galaxy S, and it uses Android's standard user interface to get text input and menu selection.

a) Communication with external resource

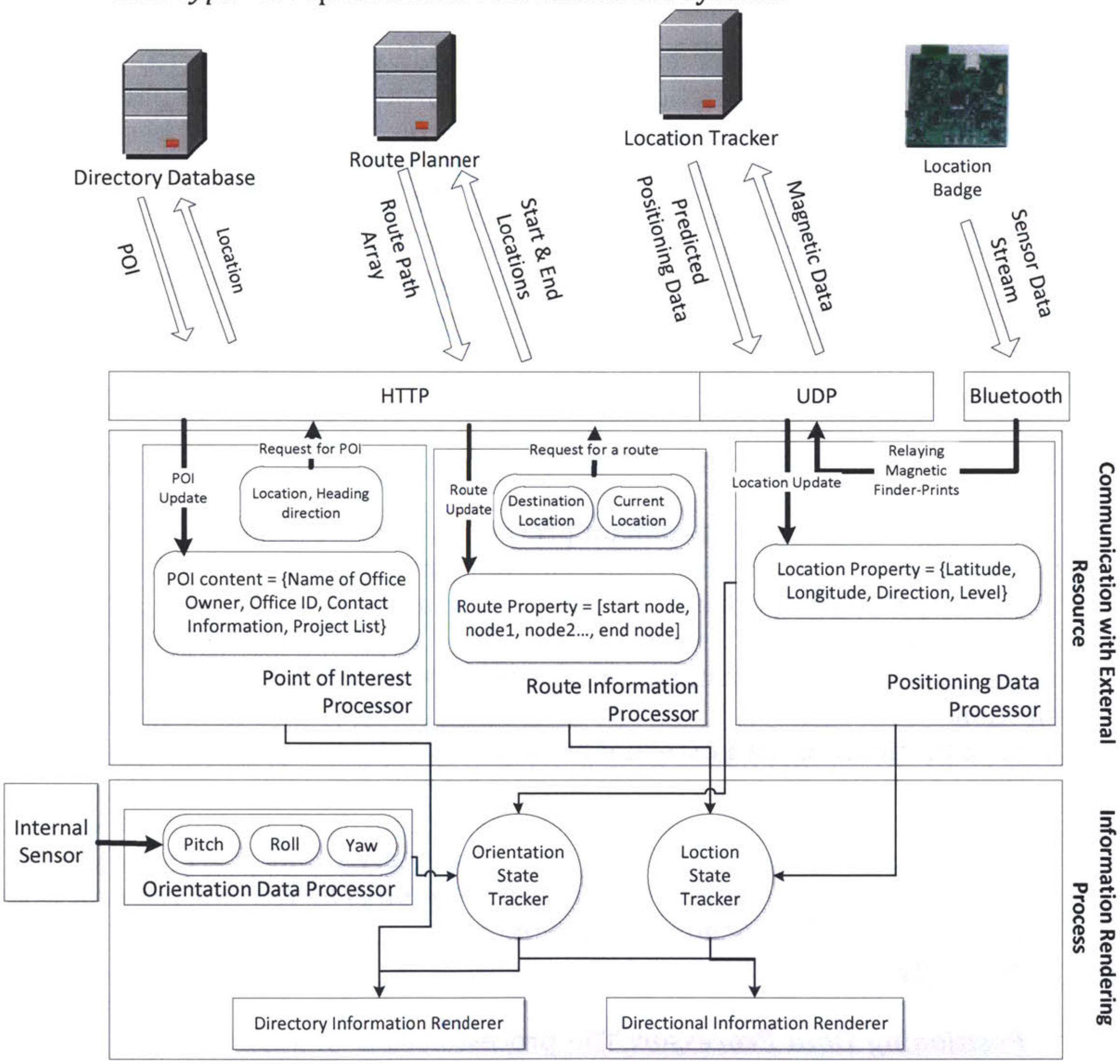
Guiding Light requires communicating with two external components, *Location Tracker* and *Route Planner,* for retrieving its location and route information, and communicating with a directory DB for retrieving point of interest (POI) information. Each communication is handled in sub processes with using a different choice of network protocol considering the criticality of reliability.

Positioning Data Processor: The processor runs in a loop to continuously update its position from an external component. Its main job is to relay magnetic fingerprint data to *Location Tracker* and gets results back after the tracker computes location. The each magnetic fingerprint is sampled and sent to the server every 250 ms, and it gets location updates every 100 ms. UDP is used for the protocol because loss of few data packets is not so critical for the system as the update is done frequently. The frequency of data retrieval is controlled by the Location Tracker.

Guiding Light gets updates of location in JSON Object data format that wraps four different data, locations in latitude, longitude, direction and level into a String message. The JSON Object consists of multiple elements of key-value pairs surrounded with curly brackets:

Position = {"lat":<double>, "lon":<double>, "direction":<double in degrees>, "level":<integer>}

<data type> is replaced with real data in the system.



Route Information Processor: The main task of this processor is to get a shortest route from the current location to the desired destination queried from an external component, *Route Planner.* Three pieces of information that are: current location and destination location in GPS coordinates, and floor information of current and destination. As Guiding Light updates current location through *Location Tracker* constantly, it is required for the user to provide destination. We use two methods for users to select target location by either choosing the Media Lab group name or choosing the name of the person who is a resident in the building. The procedures are triggered based on a user's request. The menu for providing destination is selected from context that is placed on the bottom left of the phone. It uses Android's standard UI of list menu and text input methods that are executed on the touch screen of a mobile phone.

HTTP protocol is chosen in this process because it needs more reliable network to get route information from remote component. If HTTP transaction fails, the system notifies that an error occurred during the process, and it allows the user to provide another input to the system. Otherwise, it is successfully receives route information from the server.

Messages are composed with JSON object for sending two locations to the server as following:

StartEndNodes = {"slat":<double>, "slon":<double>, "slevel":<int>, "dlat":<double>, "dlon":<double>, "dlevel":<integer>}

where prefix s and d indicates the start and destination points.

From the Route Planner, the processor receives a JSON array that consists of two or more nodes of a route. The first node is placed on the current location and the last node is placed on the destination. Intermediate nodes are placed on decision making place such as corners and intersection of the path. The nodes are to help *Directional Information Renderer* to prepare guidance information ahead of time toward the next turning points. The node is composed as following:

Node = {"Lat":<double>, "Lon":<double>, "Space":<String>, Level:<integer>}.

Multiple nodes are packed in JSON array as following: Route = [node0, node1, ..., nodeN-1, nodeN] where 0 and N indicate the starting and destination points, and 1 – N-1 are intermediate points. Data type "Space" indicates which type of space that GPS coordinate is placed at. For instance, it can be "stairs", "floor" or "elevator". This type is used in *Directional Information Renderer* to determine different types of visual guidance.

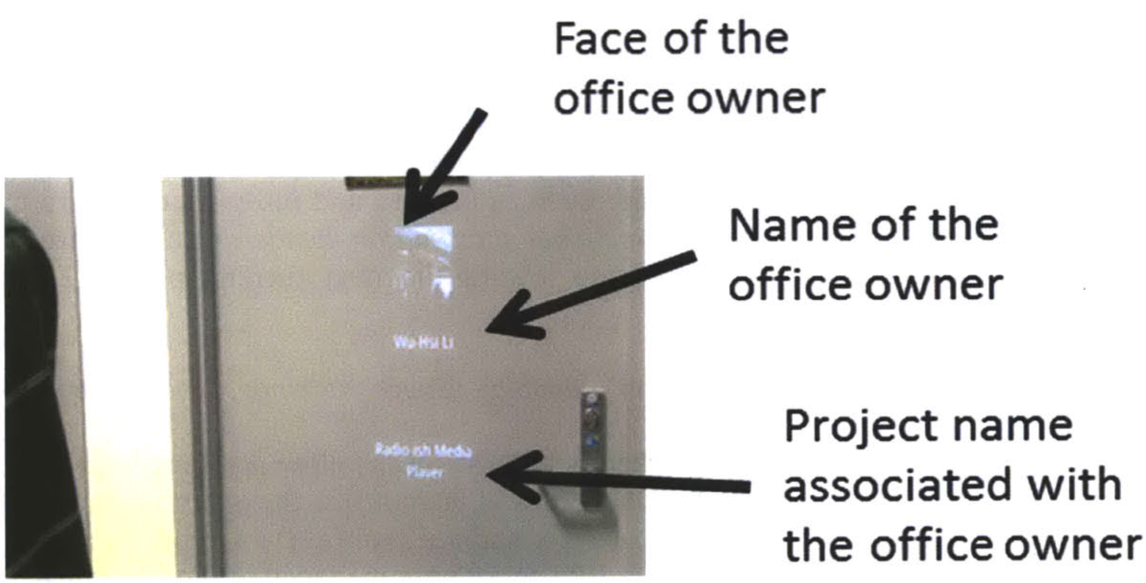
Route Information Processor: This processor handles retrieving nearby information that users might be interested in. In this version of Guiding Light, we focused on retrieving information about owners of an office. Retrieval process is triggered when pitch angle become within a certain range such that a user points the device towards on walls or on doors. Current location and facing direction are sent to Directory DB via HTTP request, and the database returns a set of JSON object described as following:

Directory = {"office_room":<String>, "picture_url":<StringURL>, "name":<String>, "projectname":<String>, "researcher":<String>}.

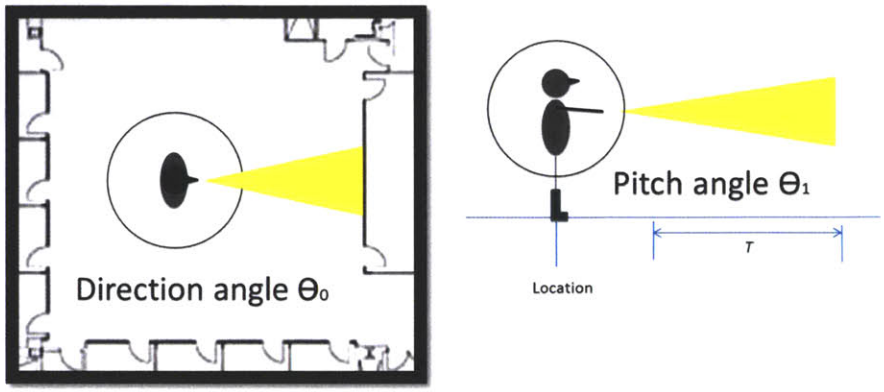
This object provides basic information about who is in the name, project name as well as the picture url which is on web. Directory information renderer takes this information and composes a screen that will be projected on office doors.

b) Information Rendering Process

After retrieving the necessary information from external components, Information Rendering Process takes care of composing visual information for navigation guidance and directory information in building; the information is processed in two different renderers, Directory Information Renderer and Directional Information Renderer. These renderers are triggered based on the combination of location and orientation of the device, and the system implements Orientation State Tracker and Location State Tracker to manage the process for triggering appropriate renderers.



Directory Information Renderer: While directional renderer is triggered when the user points Guiding Light down towards the floors, Directory Information renderer is triggered when the user points Guiding towards doors and walls. The trigger requires three pieces of information: the location of the user, heading angle Θ_0, pitch and angle Θ_1. When pitch angle is parallel to floor, the renderer prepares visual information of directory information. As we described previously, dictionary information is retrieved based on the MIT Media-Lab people directory that contains names of office owner, their contact information, email addresses, projects associated with the owners as well as URL of the owner's faces. The purpose of this renderer is to help a visitor with visual confirmation to further identify the target location by investigating the surroundings.

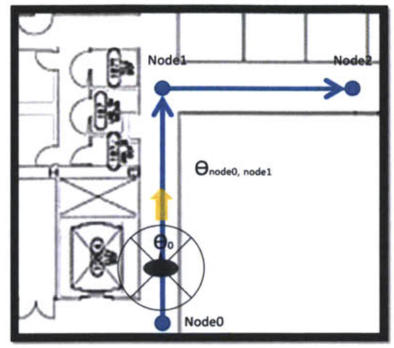


Directional Information Renderer: The directional renderer is triggered when the user points Guiding Light towards the floor. There are two conditions that determine the renderer to prepare directional information; i) projecting direction, ii) projected distance from next node. Projection direction is determined solely depending on a user's orientation, but projected distance is determined by both location of a user and the projecting angle (pitch), which alters the projected location. The detailed description of each condition will be described in the following.

i) Projecting Direction: Once its location is determined, the renderer searches for close by edges in Route and computes the angle ($\Theta_{\text{node0, node1}}$) of the direction of the nodes where a user is in between. We assume the nodes are on a plane such that the two nodes are close enough together, and well away from the poles. The equation for calculating direction is as following:

$$\Theta_{\text{node0, node1}} = atan2(X, Y)$$
$$\text{where } X = node1.lat - node0.lat,$$
$$Y = \cos(\pi/180 * node0.lat) * (node1.lon - node0.lon)$$

This angle is compared with Guiding Light's heading direction (retrieved from *Location Tracker*) and the direction of angle is rotated with Θ_{rotation} when the following condition is met:

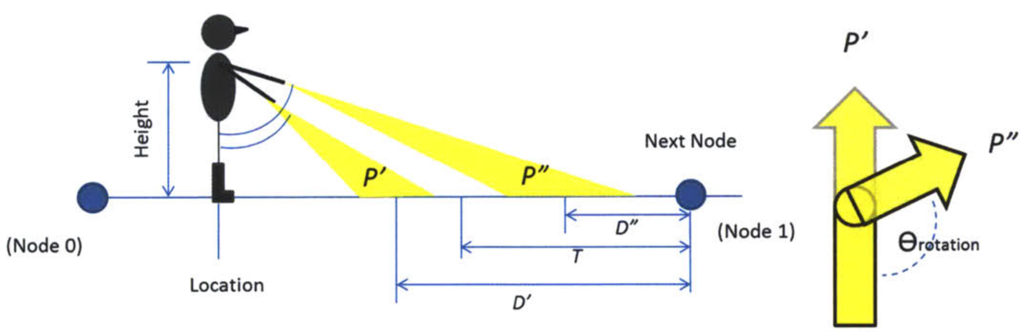


$$\theta\ rotation = \begin{cases} 0, & -\pi/4 < \theta' \leq \pi/4 \\ \pi/2, & \pi/4 < \theta' \leq \frac{3}{4}\pi \\ \pi, & \frac{3}{4}\pi < \theta' \leq -\frac{3}{4}\pi \\ -\pi/2, & -\frac{3}{4}\pi < \theta' \leq -\pi/4 \end{cases}$$

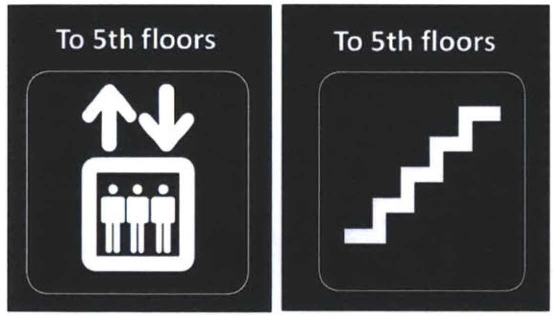
where $\Theta' = \Theta_{node0,\ node1} - \Theta_0$.

This allows the renderer to project directional information coherently toward the forward direction.

ii) Projected Distance from Next Node: Projected location is determined by two factors, the location of the projector and the angle (pitch) of the projector facing towards floor. As seen the figure below, the renderer tries to determine the distance of the projector and if it falls into a threshold, the renderer prepare appropriate arrow, i.e., if the projected location *P* is closer than a threshold distance *D,* the renderer checks if the *D* is within *T.* As shown in the figure below.



For instance, if a projection landed on P' and if the renderer checks if D' is within T, direction of the arrow (p') pointing to the Next Node is rendered (as shown in the following figure). If projection is landed on P'' AND if the if Next Noes' Space property is "floor", the renderer computes the arrow based on the direction of next edge (Node1 -> Node2). The angle can be computed using the previous equations to compute directions between two nodes. In route information, "Space" property has three options, "floor", "stairs" and "elevator". In case of stairs and floors, the next node is connected to *super node* (it will be described in Route Planner), which connects different floors on a building.



In general, while arrows are often used for moving horizontal space we use stairs and elevators to move up or down to different floors. Because the stairs and elevator only connects to different floors, the renderer prepares a direction with floor number with an appropriate method that is associated with the next node as shown in the figure.

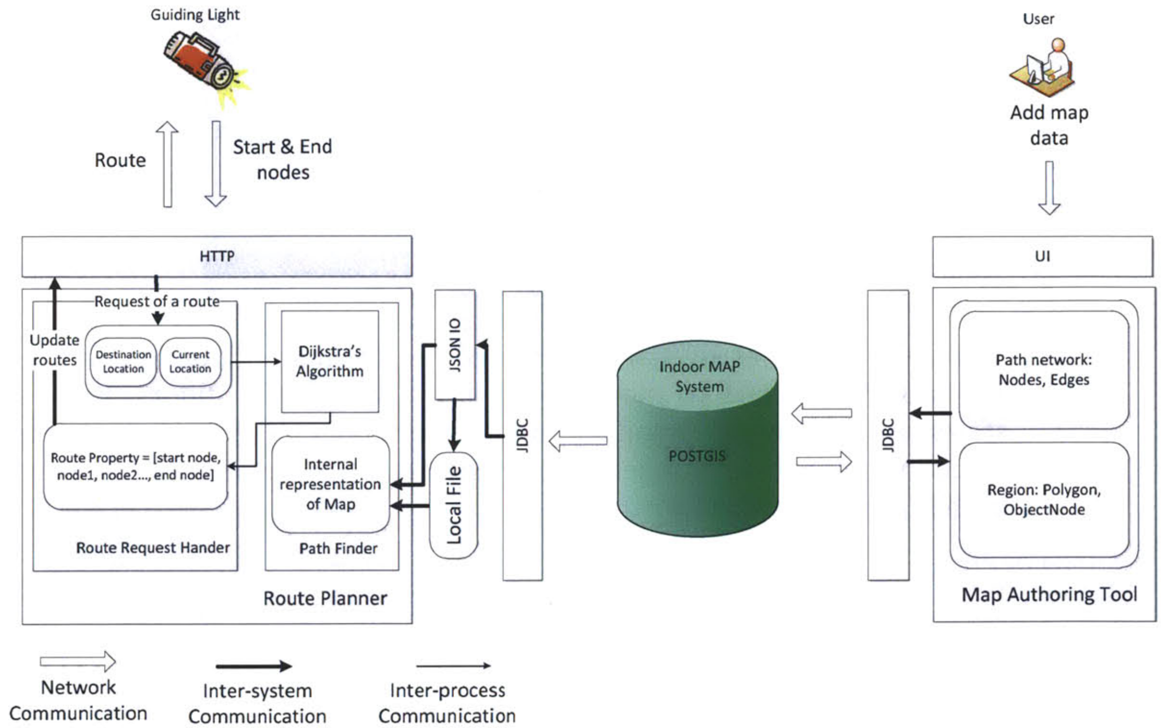
5.2 The Route Planner

In general, the route planner that we commonly see in in-car GPS navigation assistance has two systems, a map and a path finding algorithm. While path finding is a well-known graphics problem and many solutions are already available, the challenge for developing Route Planner is how to create a map that describes an indoor environment.

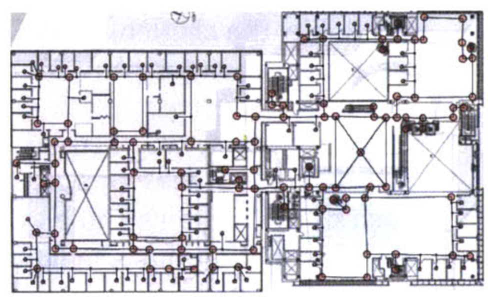
In our system, we focused on developing a system to create an indoor map, which associates with a network of pathways that connects the entire building, including the stairs and elevators. Then, we focused on a path finding algorithm to a destination that can handle the task within our map system.

5.2.1 Architecture of the Route Planner

The Route Planner consists of three sub-components, Route Planner sub-component, Indoor Map System (GIS) and Map Authoring Tool. Indoor Map System is place in the center between Route Planner and the authoring tool the systems communicate through network, which allows the sub-components running on different machines. However, Route Planner sub-component supports off-line process that reads map system cached on local file system. The following describes Indoor Map System, Authoring Tool and Route Planner.

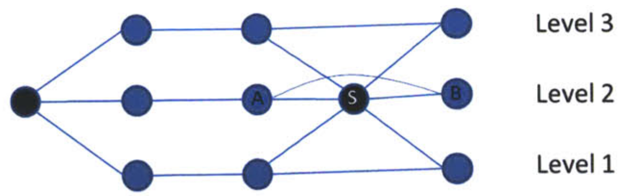


a) Indoor Map System



The purpose of Indoor Map System is to provide a map that describes indoor layout and pathway that a route planner uses it to find paths between two given locations in a building. The map consists of two data structure, Path network and Region; Path network describes the connection between pathways that links spaces in a building, and Region defines spaces such as office and meeting rooms. Path network and Region are created from a map authoring tool that provides a graphical user interface, and it is saved into a database using Postgres GIS over network. The following describes each data structure and its characteristics.

Path network: The indoor environment is different from an outdoor environment in that multiple floors exist vertically and they cannot be described with latitude because two offices are on different floors with the same latitude and longitude. So, indoor map requires introducing a "level" property that describes floor. Another difference is that floors are connected through stairs and elevators that exist on each floor but it also exist in between the floors. We introduce "super-node" in our system to connect multiple floors that is used to find path between two floors as shown in figure.



Data structure consists of nodes and edges that entire network within a building is connected. As shown in the figure above, Node A and B are connected with an edge but the nodes are also connected to Node S, super node that connects to different levels. This allows node A to be connected to other level nodes. The properties of Node and Edge are represented in JSON Object:

Node = { "ID":<long>, "Lat":<Latitude in double>, "Lon":<Longitude in double, "Level":<integer>, "Space":<String>, "Type":<String>}

Edge = {"ID":<long>, "Space":<String>, "Type":<String>, "Distance":<double>, "Node1":<Node>, "Node2":<Node>}

ID is a unique number across all geometry object, Node, Edge, ObjectNode, Polygon, and PolygonPoint. It is assigned when the each geometry object is created. Space type has three properties, "stairs", "floor" or "elevator". Type's property is for identifying the geometry type, such as "node","supernode", "edge", "objectnode", "polygon", and "polygonpoint".

Edge objects used here to keep track of the links between nodes. Edge has a property, "Distance" between "Node1" and "Node2" that is computed once when one of the connected nodes' locations are changed.

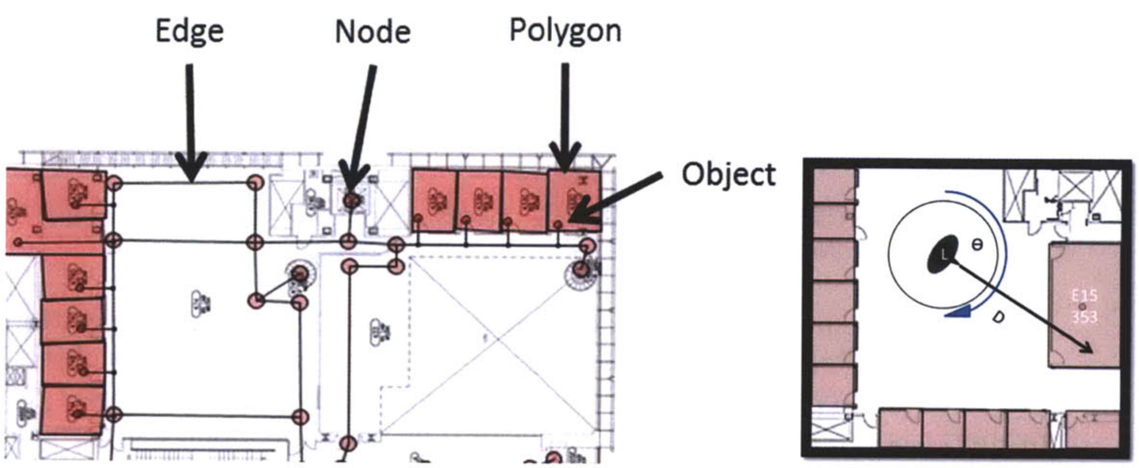
Region: The purpose of region data structure is to identify office location with assigned room number within the building. This information is used when Guiding Light requests the GPS coordinate of an office or meeting room. The data structure associate with polygon points that indicates the boundary of the region. Another geometry type, node object, is for placing a particular location of an object or utility that does not have its own object type. This object is used to identify a room number within a polygon. The data structure is described in JSON as following:

Polygon = {"ID":<double>, "PolygonPointArray":<JSONArray of PolygonPoint>, "Level":<double>}

PolygonPoint = {"ID":<double>, "Lat":<double>, "Lon":<double>, "Index":<integer>}

ObjectNode = {"ID":<double>, "Lat":<double>, "Lon":<double>, "Level":<double>, "attribute":<String>, "description":<String>, "Edge":<Edge>}

Polygon is a simple wrapper that links PolygonPoints into an array. PolygonPoint consists of location, in GPS coordinates, and index is used for ordering polygon points. ObjectNode is similar to particular Node type but it has three special property "attribute", "description" and Edge. Attribute and description is dedicated for describing an object that is located on a location. One or multiple ObjectNode can be placed inside a polygon, and these objects will be served as multiple properties of a polygon, i.e. room number. ObjectNode can association with nearby Edge such that it allows Route Planner to find path to a particular objectnode.

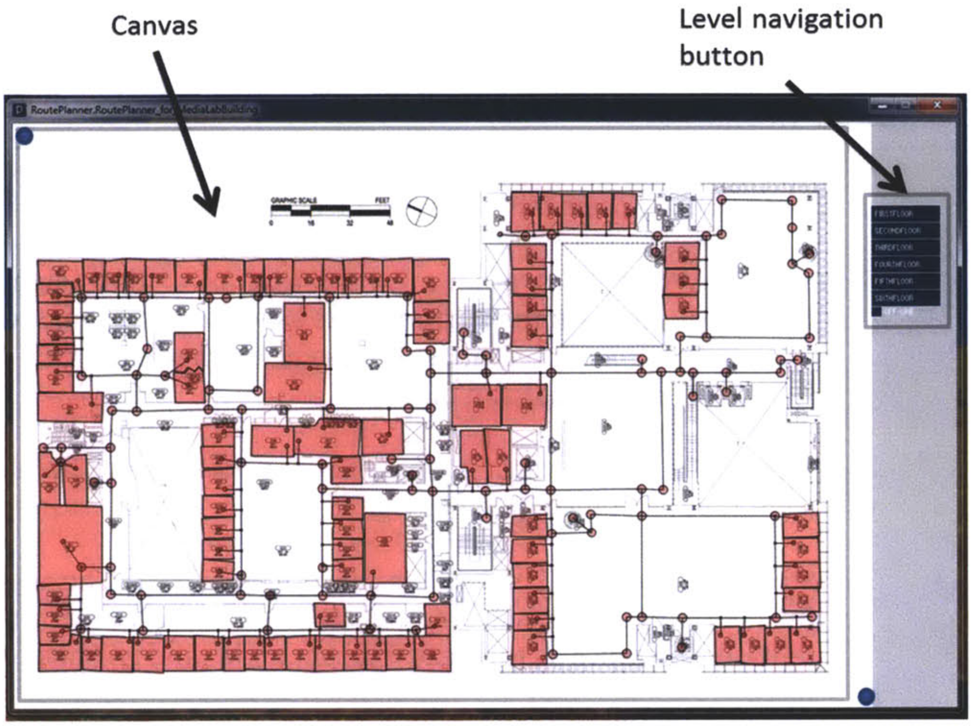


The polygons are used to identify a region where a user is facing. For instance, Room E15-353 is identified with an imaginary line *D* that points toward user's facing direction *Θ* from location *L*, and finds the closest polygon that overlaps with the imaginary line.

b) Map authoring tool

In order to provide the map, we have built a simple Indoor Map Authoring Tool that allows a user to create a map with ease. Perquisites of the tool are floor image and the GPS coordinates of left upper corner and right lower corner. GPS coordinates are not required if GIS database does not contain multiple buildings. In our system, buildings are distinguished by GPS coordinates and the connectivity of the nodes.

The tool provides interface that is similar to graphic tools that can draw nodes and object nodes by "mouse click", and relocate the nodes by dragging to other location. Edges are created by simply holding key 'e' and "dragging" the mouse from a node to another. Deleting edges and nodes is executed when a user clicks on geometry node while key 'x' is pressed. To help undo process for a user to reduce mistakes, key 'control + z' allow to undo multiple steps. The following describes the functions for manipulating the map.



- Creating a node: hold key 'n' and click on the canvas.
- Creating object node: hold key 'o' and click on the image.
- Deleting a geometry object: hold key 'x' and click on geometry object.
- Moving a geometry nodes: drag and drop on a desired place.
- Assigning attribute on object node:, a popup window show up to fill in attribute and description of it when holding key 'control' and click on a node object
- Changing floor level: click on corresponding buttons on right part of the canvas.

From our internal experiment with an untrained user, the map on this floor was created under an hour. The tool was designed to help a simple secretary to create and maintain the map with relatively small effort.

c) The Route Planner

While other sub-components are supplementary to prepare map system, the route planner is the core process that computes a route between two given locations. In this process, we use well known ***Dijkstra's algorithm*** [reference] to find a path. The algorithm is a graph search algorithm that solves a finding path for a graph a single source to a single destination-source with non-negative path cost (in our case, distance of edges), which search for a path with the shortest distance (or lowest cost) as described in the following [reference] :

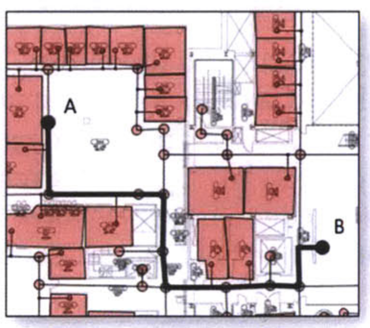
Step 1: Mark all nodes except the initial node as unvisited. Set the initial node as current. Create a set of the unvisited nodes called the unvisited set consisting of all the nodes except the initial node.

Step 2: For the current node, consider all of its unvisited neighbors and calculate their tentative distances.

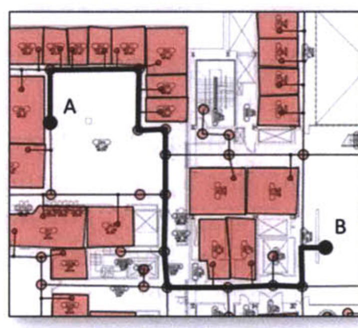
Step 3: When we are done considering all of the neighbors of the current node, mark the current node as visited and remove it from the unvisited set. A visited node will never be checked again; its distance recorded now is final and minimal.

Step 4: The next current node will be the node marked with the lowest (tentative) distance in the unvisited set.

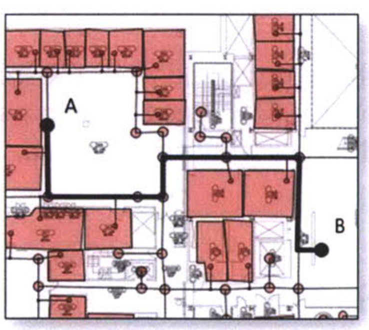
Step 5: If the unvisited set is empty, then stop. The algorithm has finished. Otherwise, set the unvisited node marked with the smallest tentative distance as the next "current node" and go back to step 2.



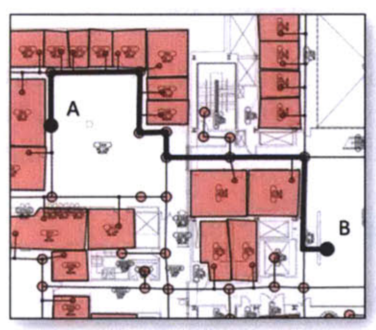
Case 1



Case 2



Case 3



Case 4

In our map system, we need to consider additional steps such that user's location may not be on a node, but Dijkstra's algorithm works with two nodes that are defined in a graph. Therefore, we need to compare four cases that take in count of two nodes from the closest edge from a starting location, and two nodes from the closest edge from a destination location as shown in the previous figure.

We often make mistakes by assigning start and end nodes from closest to two end points. However, as seen in the figure, the each case provides different path and length between location A and B and nodes assigned closest to two end points are Case 2 and the path between A and B are the farthest. Therefore, if user is not on a node, the algorithm needs to consider the four cases in order to ensure the shortest path between the two points. The Case 3 has the shortest path.

The result of the algorithm returns an array of nodes that connects between two locations, and it is sent to Guiding Light over HTTP protocol in JSON array, as following. $Route = [NODE_{start}, NODE_0, NODE_1, \ldots NODE_{N-1}, NODE_{end}]$ where NODE is defined as *Node = {"Lat":<double>, "Lon":<double>, "Space":<String>, Level:<integer>}.*

5.3 The Location Tracker

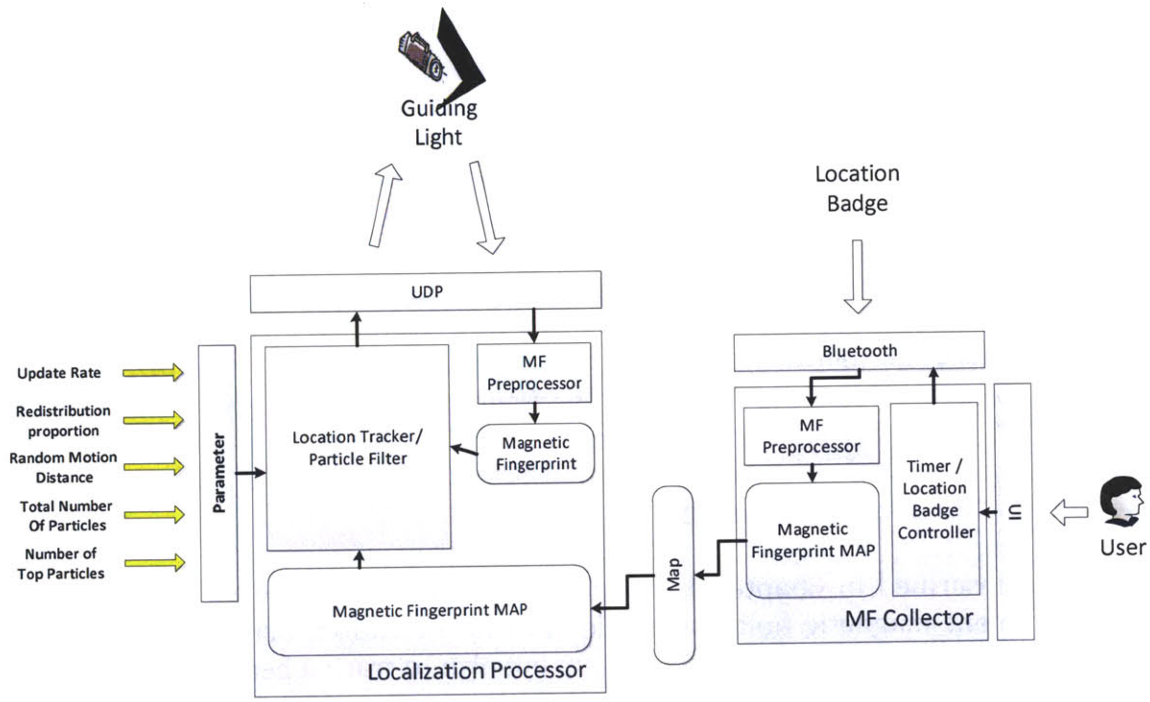
As described in Chapter 4, we built an indoor localization system that utilizes ambient magnetic fields as a reference to a location. Use of the field not only enables our system to track location but also to track a heading direction for the sensor: this is critical for an AR system that needs to acquires both direction and location.

With our new sensor that has the ability to track horizontal rotation (yaw angles) with Inertial Measurement Unit (IMU), we were able to collect a magnetic fingerprint with a direction of origin more efficiently than the previous version. This direction of origin is used for predicting calibrated direction.

Here, we are implementing a particle filter for better accuracy of location prediction. A particle filter is usually good for reducing outliers that we suffered from in previous version. This filter based localization is one of main components in our system in addition to the fingerprint collector as seen in the diagram below.

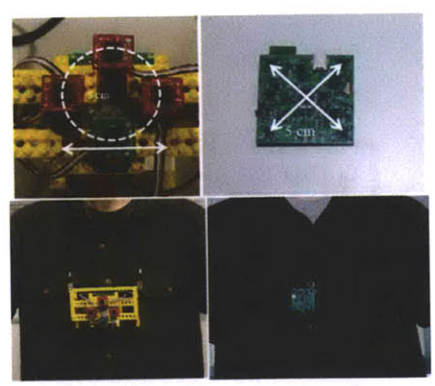
5.3.1 Architecture of the Location Tracker

The *Location Tracker* has three main sub-components, the Localization Processor, Magnetic Fingerprint Map, and Magnetic Fingerprint Collector. These components handle not only the prediction of locations but also provide a procedure for collecting magnetic fingerprints (MF) in a building space with GPS coordinates. There are a number of new developments in the system: new procedures for collecting MF data directly associated with a map user interface, a new MF map system that incorporates pitch, roll as well as GPS coordinates, a new location sensor that supports better mobility, a new preprocessor to compensate tilts for magnetic sensors, and a new tracking system that handles outliers and handle larger MF database.



a) Location Badge

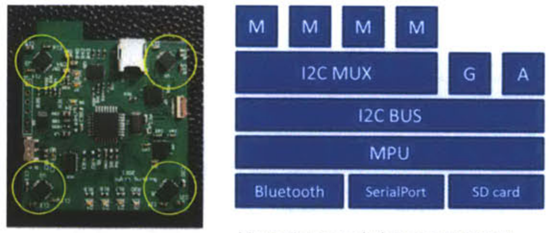
Location badge is re-designed from the previous version that sensors were attached on LEGO blocks as seen in Chapter 4. The sensor was fragile such that the structure and connectors loosen frequently that it requires constant maintenance. There is a number of changes made in the new sensor.



1) Magnetic sensor layout: The badge implements a new layout of the sensors. The distances of magnetic sensors were maintained at 5 cm. However, each sensor's orientation and layout has been changed to accommodate the shape of the new board as seen in the right picture.

1) New hardware components: The cost of the magnetic sensors is 1/10 and it comes with a price: it lacks a temperature sensor and a tilt sensor. Magnetic sensors are sensitive to temperature and need to compensate for temperature to ensure consistency. Magnetic sensors are also sensitive to its orientation and it requires tilt sensor to compensate for the error. Our new badge implements two sensors, accelerometer and gyroscope to

compensate the tilt for the magnetic sensors. However, we did not implement temperature sensor because the temperature in an indoor environment is fairly constant and we expects our sensors to work well in indoors.



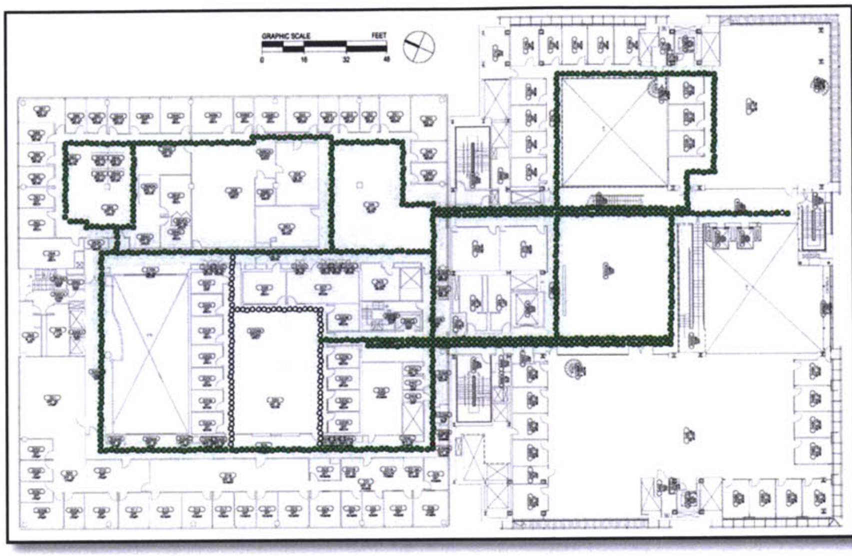
Magnetic sensor (M): 3 axes HMC5843
Gyroscope sensor (G): 3 axes ITG-3200
Accelerometer sensor (G): 3 axes ADXL345
MPU : ATmega328

2) Communication: The sensor badge implements both Bluetooth and USB based serial communication in addition to internal SD card that can potentially hold small sized fingerprints DB internally.

   One problem we noticed while deploying the badge was that the Bluetooth antenna interfered with our magnetic sensor. This added some noise in the sensor and it degraded the quality of the magnetic fingerprint. We will discuss reducing noise techniques in Localization Processor section.

b) Magnetic Fingerprint (MF) Collector and MAP

The structure of magnetic fingerprint map DB has not been changed. However, we new properties such as GPS coordinate for each fingerprint. In addition we introduce the new concept of MagCell (magnetic cell) which groups magnetic fingerprints with same GPS coordinate. The location of a MagCell is equivalent to location INDEX in our previous system, and is predefined in the process of collecting MF. Green and white circles in the map figure on the below represent MagCells. A MagCell contains about 120 fingerprints that are collected rotating a chair attached with the sensor (see in Chapter 4) 360^0.



Map User Interface: The user interface is used to plot and collect the magnetic field. The interface allows us to plot MagCell locations on a map and allows the user to create, edit and delete them, and allows the user to execute the data collection process. A green cell represents the cell with data, and a white cell represents the area to be collected.

- To create a MagCell: press '2' key to add a MagCell on the position of the red dot cursor on the map. The red dot cursor is moved by pressing the arrow buttons on the keyboard. A cursor on the map represents 60cm of the building.
- To delete a MagCell: press '0' key to delete the MagCell in the position of the red dot.
- To eeleting data in a MagCell: press 'x' key to remove data from a MagCell.
- To start data collection in a MagCell: move the red dot cursor over a MagCell and press 'n'. When the MagCell is filled with collected data, this process will replace any current data about the MagCell with the collected data. A timer is set for 10 seconds to allow for collecting the data. .
- To saving MagCells: press 's' key to save any collected data about MagCells on a file.

A reference file is prepared in the subfolder of the MF collector application defining a number of parameters such as the name and location of the file, duration for collecting data in milliseconds, a location of the image file of the map, the floor , a serial port and its baud rate for sensor communication as shown in an example:

```
port:COM13,
speed:115200,
```

samplingtime:12000,
floorlevel:3
DBfile:C:\E15.DB_3.json
LTcoordinates: [42.3609528, -71.0880250, 1,150]
RBcoordinates: [42.3603944, -71.0869139, 664,600]

LT and RB coordinates define the GPS coordinates corresponding to the pixel location on two corners of Top Left and Bottom Right of the map. This information is used to translate the x,y position in a map to correct GPS coordinates and vice versa.

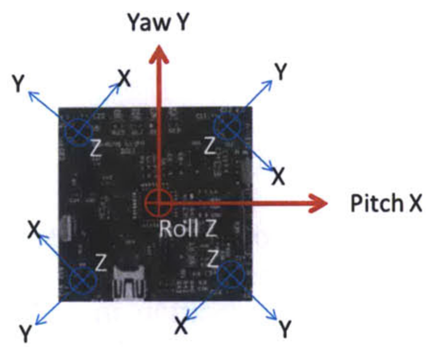
Map Data Structure: The major change in the data structure is that we introduce MagCells to organize MFs. The structure can be described as a JSON object as in the following example:

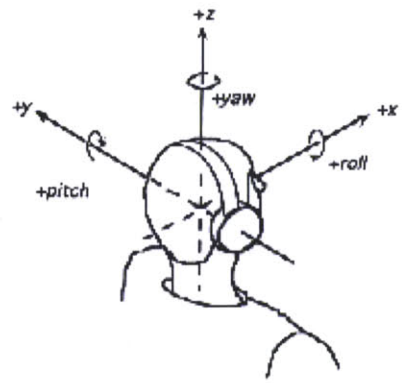
Magnetic Finger Print = {
ID:<unique ID in long>
x1:<double>, y1:<double>, z1:<double>, //from magnetic sensor 1
x2:<double>, y2:<double>, z2:<double>, //from magnetic sensor 2
x3:<double>, y3:<double>, z3:<double>, //from magnetic sensor 3
x4:<double>, y4:<double>, z4:<double>, //from magnetic sensor 4
direction:<double in degrees>, yaw<double in degrees>,
pitch:<double in degrees>, row:<double in degrees>
}

MagCell = {
ID:<unique ID in long>, lat:<double>, lon:<double>, // location of cell.
Level:<floor in integer>, // floor level
MFCell:<JSON Array of Magnetic Finger Prints> // MFs
}

The current data structure simplifies the process of indexing one location with one MagCell. With the Class wrapper of the MagCell that can handle finding Least RMS within a cell, searching MF based on GPS coordinates becomes more efficient than searching each individual MF to compute the RMSs.

Magnetic Fingerprint Preprocessing: The surface of the back of a chair is different from a human chest because the tilt angle between the sensors attached may have slight different angles. The angles create different fingerprint signature because the sensors' reading is different when the orientation is different. To overcome this problem, the sensors need to be tilt compensated. Our previous location sensor used an internal tilt compensated sensor that corrected the data based on internal sensors.





To compensate for the tilt, two angles, pitch and roll are required (but yaw is not used here because we use the magnetic fingerprint to compute yaw – the heading direction, see Chapter 4). Magnetic sensors on the board are also rotated such that the axes are turned -45, 45, 135, and -135 degrees (the sensors are starting from the left top and going clockwise) as seen in the above figure. We need to rotate the sensors to the axes that corresponding to the board axes (Pitch X and Yaw Y) and then, we compensate each sensor based on the angles of pitch and yaw.

If we let pitch, roll and yaw be *α, β, and γ* respectively; and the x, y, and z as axes be a magnetic vector, a rotation matrix can be obtained by multiplying by a basic rotation matrix. Note that the matrix reverses the given angles from pitch, roll, and yaw; therefore, we apply the matrices to reverse a given variable:

$R_{xys}(pitch, roll, yaw) \Rightarrow R_z(\gamma)\, R_x(\beta)\, R_y(\alpha) =$

$$\begin{bmatrix} -cos\gamma & sin\gamma & 0 \\ -sin\gamma & -cos\gamma & 0 \\ 0 & 0 & 0 \end{bmatrix} \begin{bmatrix} -cos\beta & 0 & -sin\beta \\ 0 & 1 & 0 \\ 0 & -sin\beta & -cos\beta \end{bmatrix} \begin{bmatrix} 1 & 0 & 0 \\ 0 & -cos\alpha & sin\alpha \\ 0 & -sin\alpha & -cos\alpha \end{bmatrix}$$

In our case, since each sensors requires the rotation to match between the sensor and the board, apply rotation matrices before and after the R_{xys} *(pitch, roll, yaw)* to reverse-rotate to the sensor's original position:

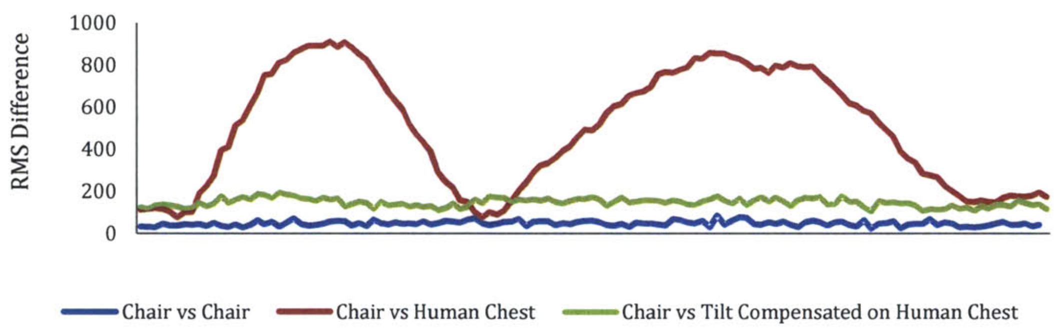
$R_{with\_sensor\_angle}$ *(pitch, roll, yaw, θ, x, y, z) =*

$$\begin{bmatrix} x' \\ y' \\ z' \end{bmatrix} = \begin{bmatrix} x \\ y \\ z \end{bmatrix} \begin{bmatrix} 1 & 0 & 0 \\ 0 & cos\theta & -sin\theta \\ 0 & sin\theta & cos\theta \end{bmatrix} Rxys\,(pitch, roll, yaw) \begin{bmatrix} 1 & 0 & 0 \\ 0 & -cos\theta & sin\theta \\ 0 & -sin\theta & -cos\theta \end{bmatrix}$$

where

$$\theta = \begin{cases} -\pi/4, & Magnetic\ sensor1 \\ \pi/4, & Magnetic\ sensor2 \\ \pi 3/4, & Magnetic\ sensor3 \\ -\pi 3/4, & Magnetic\ sensor4 \end{cases}$$

The result of x' y' z' is then compensated for and the error caused from the tilt is smaller compared to the non-compensated result as shown in the following figure (red line). The data is collected in 3 different trial by rotating in the same spot with the badge: 1st trial - rotating the location badge on back of a chair, 2nd trial - another rotation with the chair at same spot, and 3rd trial -rotating with the location badge attached to human chest . The blue line represents RMS differences between the 1st and 2nd trial over 0 to 360 degrees turn. The red line represents the RMS difference between the 1st and 3rd trials, which produce big RMS differences. After processing the tilt compensation through the algorithm the RMS differences between 1st and 3rd trial improved significantly.



c) Location Tracker

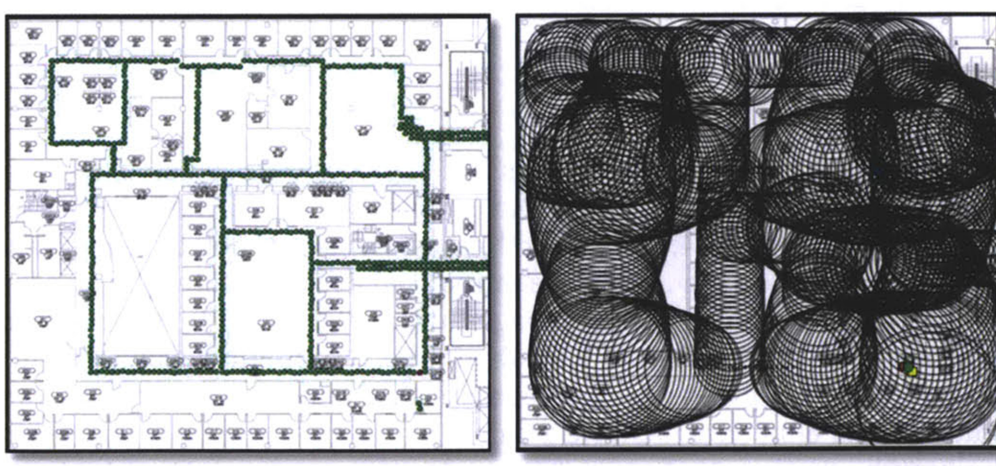
Location Tracker is the main process that provides the predicted location as well as a direction for Guiding Light. Our simpler version of Location Tracker was introduced in Chapter 4, and it used Nearest Neighborhood based on Least Root-Mean Square error. In addition, we introduced a filter to filter the measurements of the magnetic field, so that the magnitude and angle of the vector is compared in addition to the RMS to reduce noise in the system. However, this filter is still not adequate enough to remove outliers that may occur using our system. In order to fully eliminate them we are developing a particle filter that helps reduce the search space so that we only consider the nearby location that a previous prediction is made. In general Particle filters are effective for tracking objects using computer vision and localization sensors such as laser scanning [reference].

Five sub-components are associated with the Localization Processor; MF Map, MF Preprocessor, Input stream of Magnetic Fingerprints, Localization Tracker and lastly, a parameter interface that can be controlled to optimize the particle filter running inside the Location Tracker. In the later section, our main focus will be on Localization Tracker and the use of Parameters to optimize the particle filter.

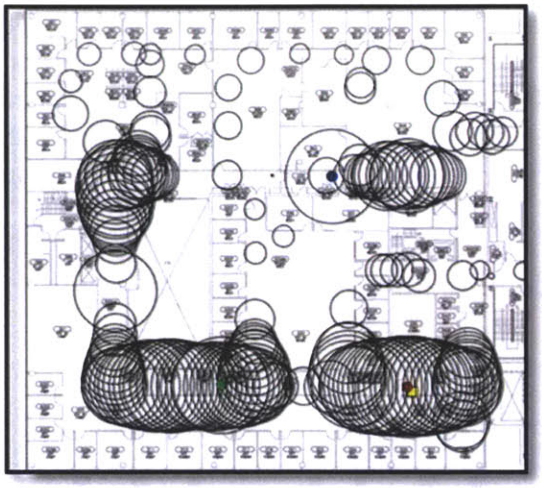
Particle Filter:

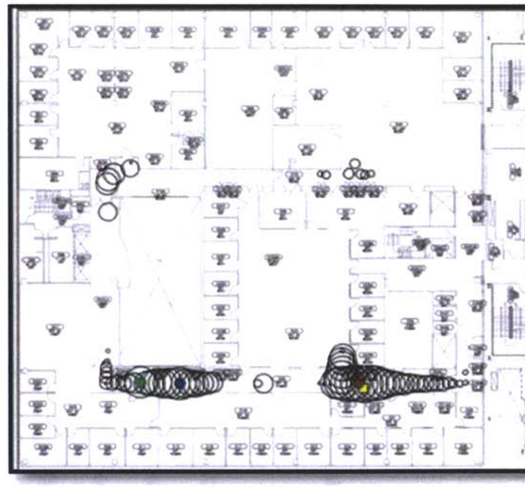
In generally speaking, particle filter is an algorithm that runs a large quantity of mini simulators (particles) in the space that is being sampled. It is a sequential Monte Carlo algorithm for a approximating location based on the distribution of particles at any point in time.

For example, we can model the location of our sensor as a continuous state variable x. We use an observed magnetic fingerprint as evidence of its location. In the initial state, it can be anywhere in the building and the probability of its location is evenly distributed over a possible x values. To determine the location, the space needs to be sampled. To do this, we evenly distributed N particles with equal probability in the space. When the badge takes a fingerprint, we multiply the probability of the particle by one over RMS between measurement and previously collected data. The graphs below describe the initial state 0, 1 from left to right. The left graph shows how particles are distributed evenly with equal probability and the right graph is the particles with probability multiplied with a scoring function (one over RMS). This changes the probability of the particles, and makes some more probable than others. (The yellow squire in the right graph is the predicted location, and red green and blue circles are indicating the 3 top particles that have high probabilities.)

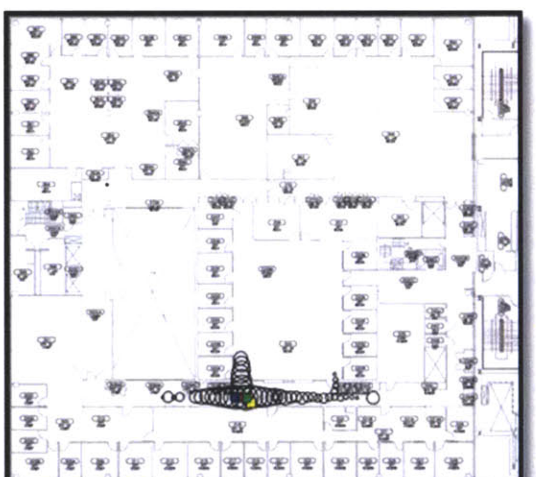


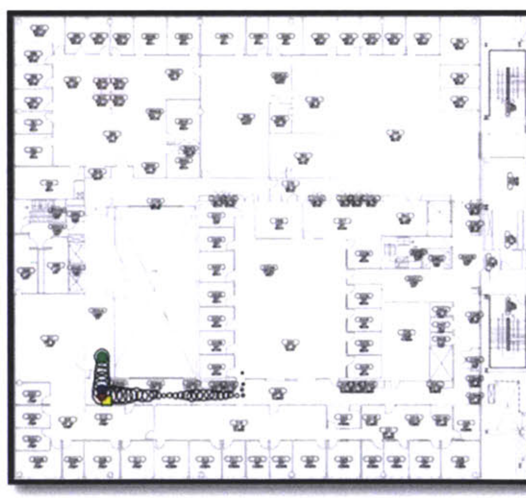
After updating particles, we can resample the distribution, removing particles that have low probabilities and duplicating particles with high probabilities. The left and right graphs are at t-1 and t time respectively, where particles of low probabilities die and the graph begin to converge.





Our location badge does not have a movement model, which typically supported by an inertial navigation sensor. In our particle filter, we relocate the particles randomly within a distance *d* to spread particles to the area that the badge might be moving towards. The left and right figures below show the converged particles that are distributed to every possible directions within a distance *d* to sample nearby locations that the sensor might be moving toward at t+1 time.

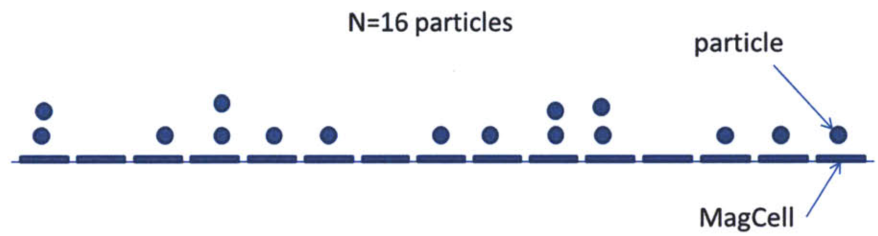




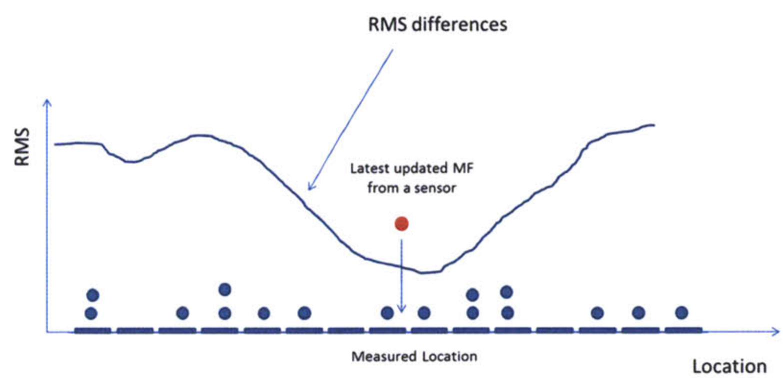
The system is essentially a state machine that keeps tracking of the previous state, while our previous system did not keep track of the previous state. Without a state machine, it is easier to scale the system in terms of number of users on the system. However, the particle filter performs better as the database of MF map gets larger as compared to the previous system because a larger MF map will generate more outliers and requires searching entire DB to find least RMS.

Implementation: In our system, the variable x is discrete as we use MagCells as the basis of magnetic fingerprint map. Particles will be distributed and calculated on the location of MagCells. The particle filter process can be described with 9 steps with 5 parameters, *N* (number of particles), *T* (top scored particles), *D* (movement radius), *U* (Update frequency), *R* (re-distribution proportion ratio):

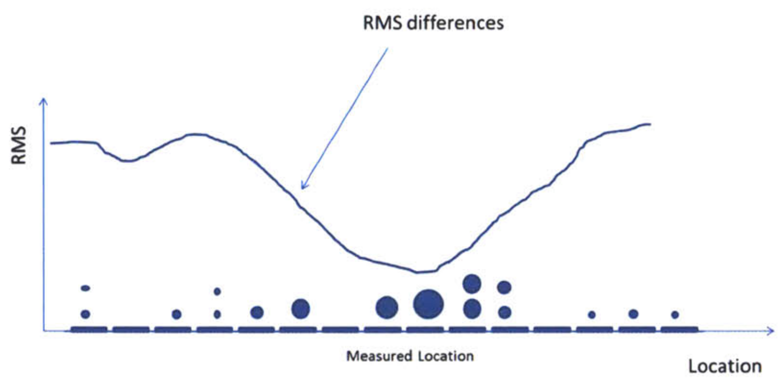
Step 1: Distribute *N* particles randomly onto MagCells in the MF Map



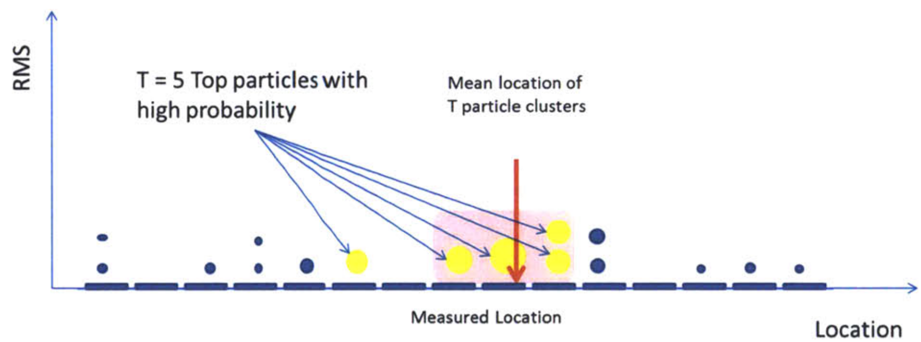
Step 2: For each MagCell that particles were distributed onto, calculate RMS difference against most recently updated MF from a sensor.



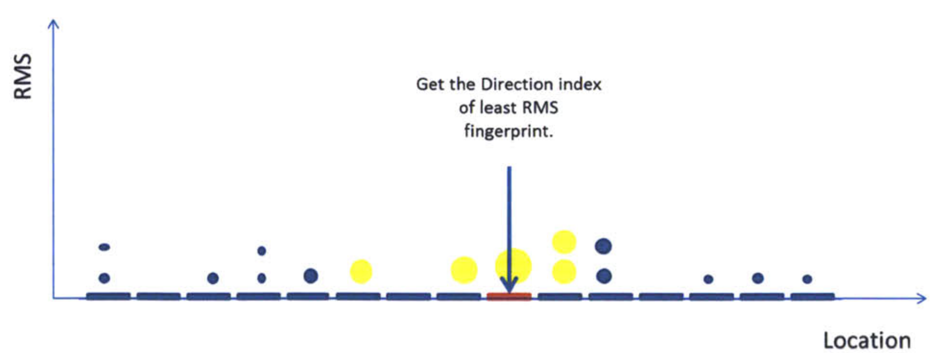
Step 3: Update the weight and probability of each particle based on the RMS of Magcell that associated with each particle. Assign increasing weights (probabilities) to each particle with decreasing RMS error – a low RMS error means a higher weight.



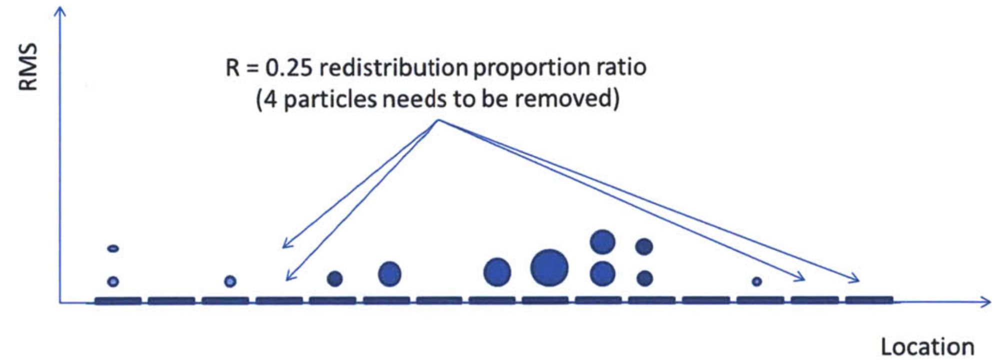
Step 4: Cluster particles that are in top T particles with highest probabilities and return the center computed from the average of these T particles as the predicted location.



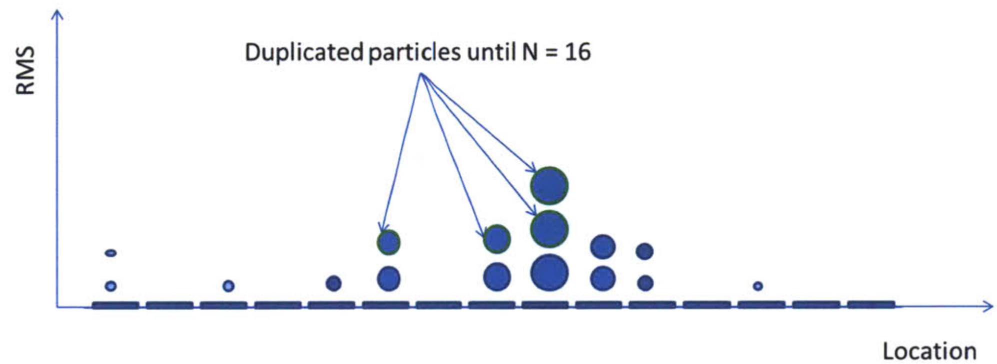
Step 5: Within the vicinity of the highest scored particles, find the least RMS fingerprint in the MagCell. Then, set the predicted direction with this identified fingerprint's direction.



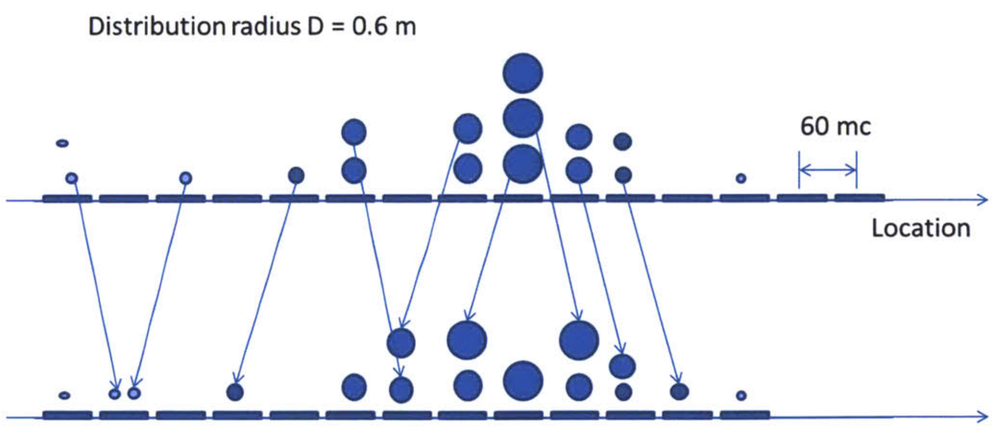
Step 6: Remove low probability particles that are within a redistribution proportion ratio R.



Step 7: Duplicate high scored particles on top of same location until the number of the particles are equal to *N*.



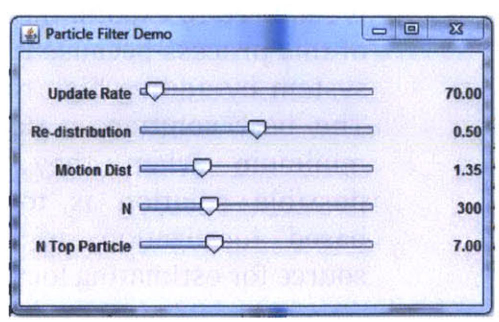
Step 8: Distribute all particles randomly within a radius *D.*



Step 9: Sleep for $1000/U$ milliseconds and go to Step 2.

Pseudo Code of particle filter applied in the system:

```
Function Particle Filter (wifi gps , MagneticFeature mf)

        If initializing filter // Step 1.
                For each position in database
                        Create Particle containing a Magcell and a probability
                        Particles.append(Particle)

        //get MagCellLocations
        For each magcell in database
                Clear magCellLocations
                If magcell contains Particles
                        Remove particles from magcell

        For each particle in Particles
                Add particle.magCell to magCellLocations
                Add particle to magcell

        //evaluate only RMS
        For each magcell in magCellLocations
                magcell.getLeastRMS //Step 2
                totalRMS = totalRMS + 1/leastRMS // Step 3

        Normalize particles probabilities with totalRMS
        Cluster particles and estimate location //Step 4
        Get L index from MagCell that has highest propability particle //Step 5


        //redistribute Particles by Proportion
        For each particles in particles.size //Step 6
                If particle probability too low
                        Remove particle

        For each particle in removedparticles // Step 7
                Add particle to new MagCell
                Reset probability


        //movementModel
        For each particle in particles //Step 8
                Move particle to new magcell d distance away where d<= a setdistance && >= 0
```



Parameters of Particle Filter: In the description of particle filter in our system, we used five parameters to control the performance of the prediction. The parameters are:

i) "Update Rate" parameter updates the prediction of particle filter every R milliseconds. In general the faster speed of update rate will produce accurate positioning prediction.

ii) "Re-distribution" parameter control the proportion of the lower probability particles to be removed from the system in Step 6 For instance, when the parameter is set to 0.5, the lower half of the particles with lower probability particles will be removed. However, after the particles are removed, the algorithm redistributes the particles to the location of the higher probability particles. In general, if the MF DB is noisy, reducing the parameter will be less likely to fall into local minimum.

iii) "Motion Dist" parameter defines the radius (in meter) of the particles to be randomly distributed in Step 8. In general, lowering the parameter will reduce the noise of prediction in the system. However, if there is little motion in particles, the particles will not be sensitive to the changes of the MF from the badge.

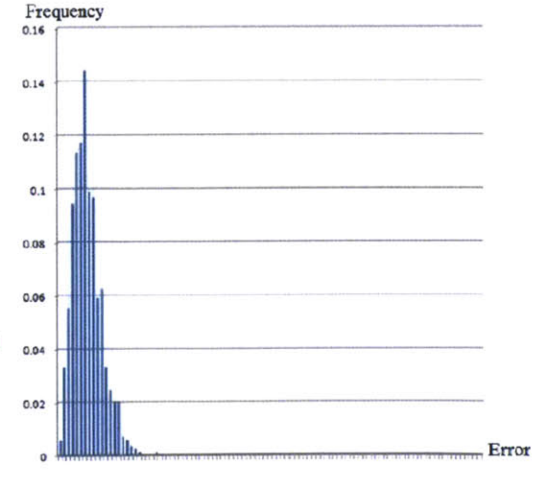
iv) "N" defines the total number of particles running in the system. In general more particles produce a more accurate estimation of position of the location sensor, in indoor environment, 200- 300 particles produce good performance.

v) "N Top Particles" is the number of top particles that have high probabilities. The particles are mainly considered to determine the prediction estimations. In high SNR systems, lower number of top particles can produce good enough predictions (that is only rely on the highest probability particle), but in low SNR systems, considering a number of top particles work as low pass filter effect.

From our experience with Media-Lab in E14 and E15 buildings on corridor environment, the optimal ranges of the parameters are:

Update Rate = 70 – 100 ms.
Re-distribution = 0.25 – 0.5
Motion Dist = 1.3 – 1.7
N = 200- 300
N Top Particle = 3 – 7

Other observations about the particle filter: Particle filters often fall into local minima because they only consider searching for answers from nearby last predicted area. In order to reduce the possibility, re-distributing particle method is required to expand the search space. However, this requires careful execution of this process because it can hurt the system by adding high random noise. The best solution is detecting local minimum when they occur. One possible solution is to add WLAN based localization as a secondary source for estimating location.



Our experiment with WLAN based

localization shows that 90% of the location prediction error fall under 11.5 m, but maximum error is 21 m as shown in the right graph. If the distance between the WLAN prediction and particle filter's prediction is greater than 11.5 m, the particle filer can start re-distributing particles to wider range to get out of the local minima. Another phenomenon with local minima we observed with the particle filter is that particles stuck on a local minimum and particles do not move, while the location badge in motion. This particular problem can be solved by examining the location badge's accelerometer. If accelerometer data is fluctuating while particles are not moving, the particles can be re-distributed to get resolve the problem. This can be used in reversed way: the accelerometer is not reporting any significant movement, but particle filter continues to move.

6 Evaluation

6.1 Overview

As we stated early on, the motivation for designing Guiding Light and our key design principle choosing our user interface were to examine the causality between visual attention and users' engagement level in traveling surroundings. The common belief is that reducing visual attention division will reduce accidents caused by the distraction from surroundings and improve the acquisition of spatial knowledge. On other hand, we attempt to identify the psychological problem that causes overreliance on automated systems that can cause the traveler to be disengaged from his surroundings. The purpose of the experiment discussed in this chapter is to examine the actual causalities and correlation between these physiological and psychological factors on engagement level.

6.2 Hypothesis

Here, we examine visual attention division and excessive reliance on an automated guiding system that may disengage the user from the surroundings. We frame the problem as considerations of both the physical and the psychological aspects of engaging in the environment – the users must physically keep their "eyes on the road" and mentally process all the details of their surroundings.

Our approach addresses these problems by i) providing a new visual interface that offers a projection-based augmented reality presentation of guidance information as opposed to screen-based, and by ii) providing a sense of control in route selection in the context of pedestrian navigation. We hypothesized that a system that forced users to look at their surroundings would be more effective than a system that encouraged them to constantly look at a screen.

We hypothesized that H.1 a projection-based system would encourage users to look at their surroundings more often while using the device and maneuver around obstacles more effectively, compared to a system that allowed them to constantly look at a small screen. We also hypothesized that H.2 giving users a choice of route and thus instilling a sense of control in them would engage them more in their environment than when not offering an alternative route to choose. This would result in better acquisition of spatial knowledge and give users a better sense of direction in their environment.

In order to test our hypotheses, we introduced a methodology for testing people's engagement level by providing a tour of a new building guided by either a projection or screen-based system and giving some people freedom to select their routes and others no choice. We then measured how they performed in finding their way with the device during the tour and tested their ability to navigate inside of the building afterwards using only spatial knowledge they acquired during the tour.

In the following, we provide a detailed description of our evaluation methodology. Finally, we present the results of our experiment and the conclusions of our study.

6.3 Methodology

To test our hypothesis, we developed a projection-based AR guidance system as our platform to test if the engagement level of the users increases when we project directions onto surfaces along the route. As a counter control, we developed a screen-based guidance mobile system on a tablet computer. Both systems occasionally provide a feature to inform users about two alternative paths and allow them choose one. Thus, we have two independent variables, device type and whether the user has choice or not, in a 2x2 experiment.

We tested engagement level by comparing measurements of travel time and path length to given landmarks previously visited using our two devices. If the subjects were more engaged with the environment while using the devices, then they would have an easier time revisiting routes from the previously visited areas.

The experiment consisted of two parts. During the first phase, subjects learn their way around the area, and during the second they are tested on the knowledge they retained. However, instead of asking subjects to find their way on the same paths, we asked them to apply their knowledge to find a more direct path between two non-consecutive landmarks. If the subjects were more engaged in the environment while learning the area, they should be able to find the best path between two points more quickly.

6.4 Interface descriptions for the comparison groups

6.4.1 Screen Based Navigation Group

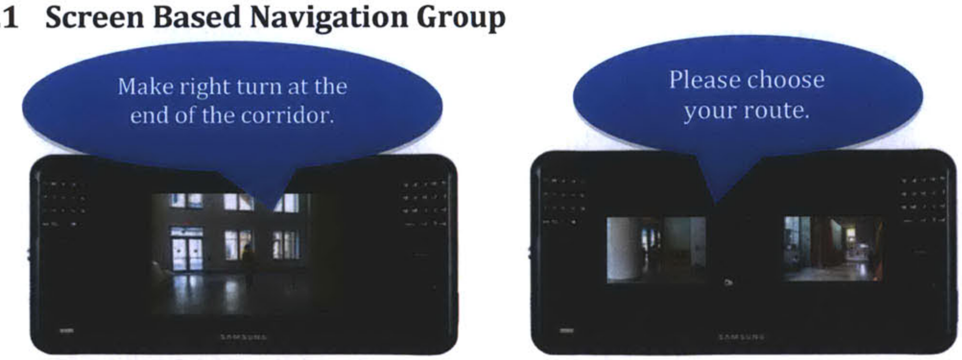


Figure 6.2. Screen-based guidance system on a tablet.

This tablet-based system gives visual and audio cues on where to go. The user looks at the image and sees a person walking in a certain direction. The image was taken with a real person walking through the path. Then by directly comparing the image to the immediate surroundings, the user walks towards the next destination. Furthermore, although directions are primarily given through images, the device also provides spoken direction using built-in text-to-speech. An experimenter manually updates users' current locations and then the system updates the guidance based on where the user is. The experimenter triggers a new picture every time the user passes by the place in the previous picture to let him easily find the matching scene on the path. When it is time to make a choice, two images appear and the tablet will give an audio description of each. The two images were also easily seen from where the picture was triggered.

We used a Samsung ultra-mobile personal computer (UMPC) and a Samsung phone to realize this system. The phone served as a client side application, sending the user's current position and route choices to the UMPC to update the image. In this system, the client phone and the UMPC communicate through a Bluetooth connection. In the rest of the paper, we will refer to this device as "Tablet".

6.4.2 Projection and AR Based Navigation System

The other device was a projection-based navigation device that uses predefined tour routes to project visible arrows into the surroundings.

When the user is supposed to take an elevator or stairs, an elevator or stair image will pop up with text telling the user to go to a certain floor. When it is time to make a choice, two arrows appear and the user has to walk in the direction of an arrow to make the choice. The experimenter will then update the user's choice and position and continue to guide the user in the correct direction. This guidance system is based on Guiding Light.

Figure 6.3. A projection-based AR guidance system.

We used Samsung Galaxy S phones with a mini-projector attached to realize this system. There is a client side system (held by the experimenter) that communicates to the server side (held by the subject) with Wi-Fi. As the client side updates the user's position, the server side receives all the relevant information and presents it to the user in a minimalistic way – either through a simple image or an arrow.

Although we again used wireless remote control to update the location of this projector-based system, it is based on a working prototype we have developed. In the rest of this section, we will refer to this device as "Projector".

There are two reasons behind updating the position manually. First, the experiment is meant to evaluate different types of user interfaces and the results can be greatly affected by positioning error. Second, we are not inclined to measure magnetic fingerprints in Stata Center (the site for the experiment) because it is too large for our limited resources to get magnetic fields within the time scope. Manual updates allow us to isolate noise from the effects of the examining factors, visual condition vs choice condition, and thus our result minimizes these external factors that can render degrading the quality of the experiment result.

6.5 Experiment Setup

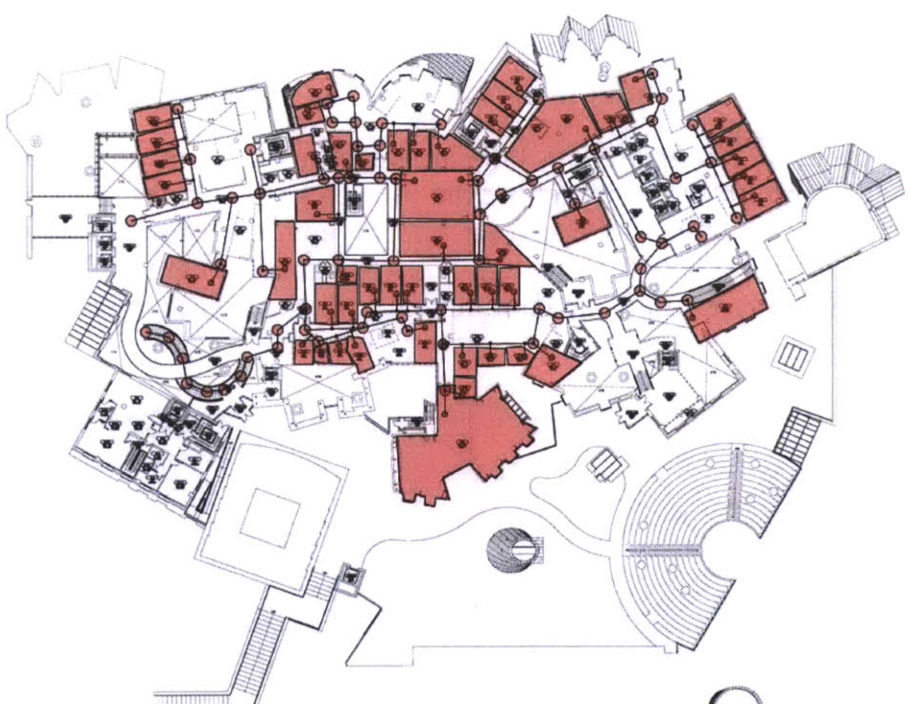


Figure 6.4. Building floor layout

6.5.1 Recruited Subjects

There were 60 subjects in this study as shown in the Table 1. All subjects were tourists who were interested in a tour of the building; we actively recruited subjects by handing out fliers advertising our free tour and personally talking to them. The participant pool was made up of 42 males and 18 females, ranging from 12 years old to 67 years old. As we were looking for tourists, some participants were prospective students.

Subject recruitment was carefully considered to provide equal distribution of gender, age, and occupation, as these factors can influence the results. People with vision disabilities were not be considered since our system design is inadequate for supporting people with visual impairment. In addition, only subjects who are not familiar with the interior of Stata Center were considered, as the experiment was to be conducted in these buildings.

N = 60		**Choice or Scale (1 – 7)**
Gender	Male = 42, Female = 18	Male/Female
Age	31.15 (SD = 14.74) (Min = 12, Max = 67)	
Occupation	Students, MD, teachers, engineer, housewife, retired, tour guide, etc.	
Education level	Jr. High, high school, undergrads, graduates, Ph.D.	
Familiarity of layout of the building	1.57 (SD = .87)	1 (unfamiliar) – 7 (very familiar)
Sense of direction (self-report)	4.54 (SD = 1.29)	1 (poor) – 7 (very good sense of direction)
Being Lost	3.6 (SD = 1.46)	1 (never) – 7 (very often)
Visit new places	4.31 (SD = 1.23)	1 (almost never) – 7 (daily)
Have car-nav GPS	Yes = 32 -61%	Yes/No
Used car-nav GPS	Yes = 44 -84%	Yes/No
Play navigation related video games	2.74 (SD = 1.91)	1 (never) – 7 (very often)

Table 6.1. Participant's information and self-report of sense of direction.

Subjects used the system in each condition, going through two-task setting phases, a navigation task with the devices and a navigation task without the device. Before getting into the first phase, independent measures were self-rated sense of direction, and general questions related to subjects' occupation and life-style to learn about their prior experience and skills in indoor and outdoor navigation. This was followed by basic training of how to use the device.

All participants underwent both phases, as they are designed to go hand in hand. However, we split them up into groups. First we divided them by device: one group used the Projector and the other used the Tablet computer. Then within each group we split them into choice and non-choice groups, i.e. one group chose their own routes and the other group had no such choice. Then, we further subdivided the choice and non-choice condition groups into actual and perceived control groups: actual control groups made choices that changed the path of their tour, whereas perceived control groups made an illusory choice - regardless of which route option they chose, they followed the same predefined path through the entire tour.

6.5.2 Experiment Tasks

Phase one: *Tour.* Phase one is designed to measure usability of the device by asking subjects to use the device to find a number of designated destinations, so we asked the subject to follow the device's directions to six landmarks in an architecturally confusing famous building, STATA CENTER. We chose to purposely hide the hypothesis of the experiment as to prevent subjects from intentionally memorizing details that they wouldn't have memorized normally. For the dependent measurement we measured (i) success of completion, (ii) time of travel, (iii) head orientation, (iv) number of errors, (v) number of stops, (iv) and confusion level – the dependent measurements are explained in the following section.

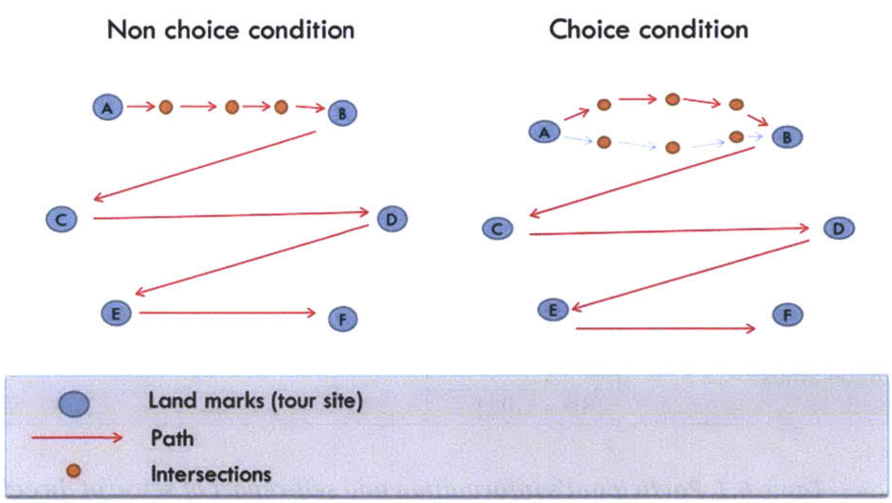
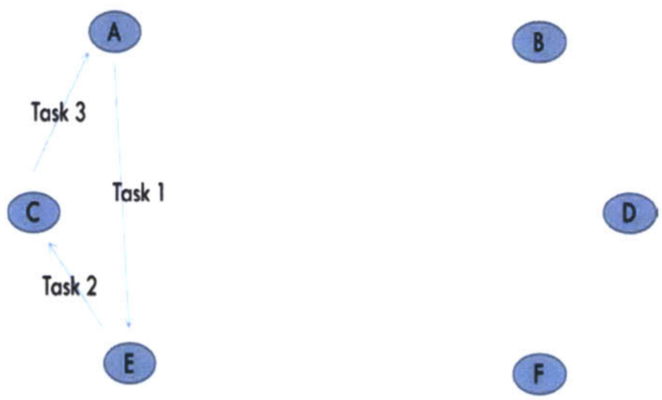


Figure 6.5. Tour and Task phase routes

Phase two: *Test.* Phase two was designed to assess subjects' engagement level in the task domain of navigation. The subjects were asked to find their way to three locations that were introduced in the tour to which a direct path had not been introduced, i.e. the locations were not consecutive in the tour. Our hypothesis was that subjects who were mindfully engaged in the process of navigation, i.e. chose their paths, would have a better sense of direction and remember more details of the environment, thus rendering them better in handling navigation tasks in an environment they have been through once before. For the dependent measurement we measured (i) success of completion, (ii) time of each task, (v) number of stops, (vi) confusion level, and (vii) traveled path length.



The measurement (iii), (iv) conducted in *Phase two* are omitted because (iii – head orientation) and (iv – number of errors) associate with the use of devices such that we measure (iii) to see how much users required to see the device, and measure (iv) to see how much errors that users made based on the given guidance instruction. Likewise, the (vii – path length) is omitted in *Phase one* because the length was controlled by our experiment setup and there is no room for changes made by the subjects.

Measurements

The following measurements were taken to see how efficiently subjects used the device and how each device affected their spatial knowledge of the building. The measurements are evaluated at 9 different places where 6 (traveling to 6 different landmarks) of them are in the Phase one, and 3 (finding 3 different locations) or them are in the Phase two.

(i) ***Successful completion.*** A binary system, this was used to record whether the subject was successful in finding his destination. This was measured in both phases in each task.

(ii) ***Time of travel.*** This measure was the length of time that the subject took to travel from one landmark to the next. In phase one, a long travel time would indicate a lot of pausing to understand the device's instructions, indicating a less effective device. In phase two, a long travel time would mean wandering, suggesting the subject does not have a good grasp of the layout of the building. This guess can be corroborated by the length of the path. This was measured in both phases.

(iii) ***Head-orientation.*** On a one to ten scale, this measured how much the subject focused on the device. Low numbers mean the subject did not look at his surroundings, while high numbers mean that he looked around a lot and not at the device. 5 indicates that the user spend half of the time looking at device and half of time looking at surroundings. This was only measured in phase one.

(iv) ***Number of errors.*** Only used in phase one, this includes missed turns and wrong turns that the subject made. We start the number from 0 and add one at each task each time a user makes a mistake. We also included other errors here, which refer to error made on the controller's part, as they sometimes made mistakes with the right timing for directions.

(v) ***Number of stops.*** This measured how many times each person stopped to look around and figure out where they were. We start the number from 0 and add one at each task each time when a user makes a stop. This was measured in both phases.

(vi) ***Confusion.*** This was measured on a one to ten scale. In phase one, this was measured on how confused the subject was by the device's instructions. In phase two, this measured the subject's wandering. If he knew where to go, then the number would be low, but if he was unsure of himself, even if he got the right path on the first try, his number would be higher. Confusion was evaluated by combining the value of (ii), (iv), and (v).

(vii) ***Path length.*** Only in phase two, this measured how much the subject wandered around. This was measured on a one to ten scale. We took a path length of five to mean that the subject's path was about as long as the path that the tour took him on. In other words, if the path length is five and new paths number is zero, then the subject took the same exact path as in the tour; if the path length is five and there are multiple new paths, then he was likely close to finding a shortcut but took a wrong turn and wandered.

6.5.3 Experiment

Each participant was assigned to a device and a group (choice or non-choice). Before beginning the experiment, they filled out a questionnaire for statistical information such as age, gender, and occupation. The questionnaire also had questions to determine how well they knew the building, whether they had experience using GPS systems, and how they would rate their sense of direction. After this questionnaire, participants underwent our tour. We had a team of three working with them. During the experiment, one member of the team, the tour guide, walked slightly behind the subject so as not to affect his following of directions as he walked to each landmark. The tour guide gave a history of the landmarks and also talked about the general history and architecture of the building as they walked. Another member, the recorder, observed the subject and made the proper measurements, and the final member, the controller, handled the device as the subject was walking, so that the directions were timed properly.

Every choice-group user determined the path for his corresponding non-choice partner. As the choice-user went on the tour and chose which route to take, the recorder noted each choice so that the controller and tour guide would know for the next user who did not have a choice. This way, the actual path was controlled.

The participant then moved onto phase two of the experiment. Similar to phase one, we followed the subjects around as they attempted to find the shortest path and recorded information about their knowledge of the building. Only the recorder and the subject walked around; the recorder was not allowed to give any clues about the location of the landmarks. If after five minutes, the subject had no idea where the next landmark was, we would ask the subject to give up. We had three landmarks for them to find; when they were finished we had a final questionnaire for them to fill out asking them to reevaluate their sense of direction and how well they knew the building.

6.6 Results

We have conducted unpaired *t-tests* between two groups (choice vs. non-choice and Tablet vs. Projector groups) and analyzed them with two-tailed *P* values.

6.6.1 *Measurements during the tour phase*

We considered three different variables in the tour phase- i) errors, where we consider the number of wrong turns and missed turns the user makes, ii) confusion, which combines the number of stops made by the subjects with an evaluation from the experimenter, and iii) head orientation, which evaluates how frequently the users look at the guidance information.

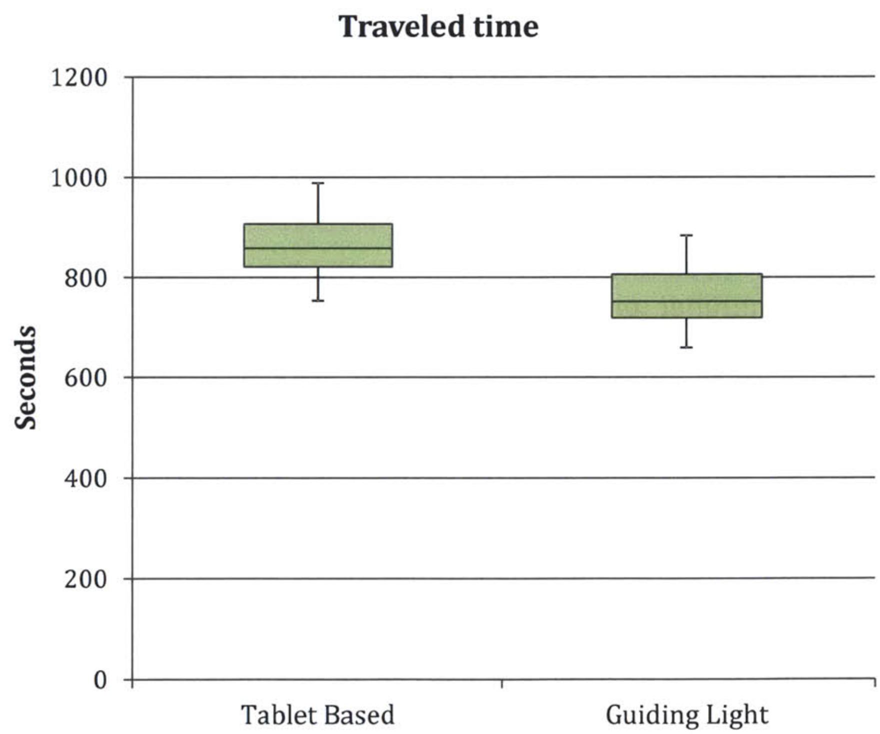
Tablet vs. Projector: Fewer missed and wrong turns for Projector were observed because explicit arrow instructions told the user exactly where to go next.

People in the Projector group spent less time looking at the actual device as shown in Table 6.2. The Tablet group had to explicitly look at the screen for a long time to figure out where the device was directing them because they had to compare the device's images with the surroundings. In contrast, Projector users merely had to follow an arrow. As a result, Projector users dealt with stairs much better than Tablet users – we saw some Tablet users trip on the stairs. Projector users were more focused on the actual path, despite the need to frequently and briefly look at the arrows to check for arrow changes. If we provide some pre-alert (vibration or beep sounds) before each arrow change, Projector users may not have to look at the arrow as frequently, further improving the usability of Projector.

	Tablet (n = 34)		Projector (n = 26)		Result	
	Mean	SD	Mean	SD	*p*-value	*t*-value
Error	1.6	0.88	0.68	1.77	**0.0116**	2.6
Head Orientation	31.31	10.02	22.46	8.70	**0.0007**	3.585

Table 6.2. Observation during the task - between Tablet vs. Guiding-Light. In the bar graph, the values of y axes are normalized with respect to the Projector. (lower the better)

In terms of travel time, people in the Projector group spent significantly less time ($p = 0.0015$) walking between landmarks as shown in the Figure 6.8 in the graph and the table. We investigated the effects of prior experience with GPS ($p = 0.8201$), virtual navigation (in video games, for example) ($p = 0.1292$), gender ($p = 0.8742$) and age ($p = 0.6921$), and we found no correlation respect to the travel time difference in Tablet and Projector group.



	Tablet (n=34)		Projector (n=26)		Result	
	Mean	SD	Mean	SD	*p*-value	*t*-value

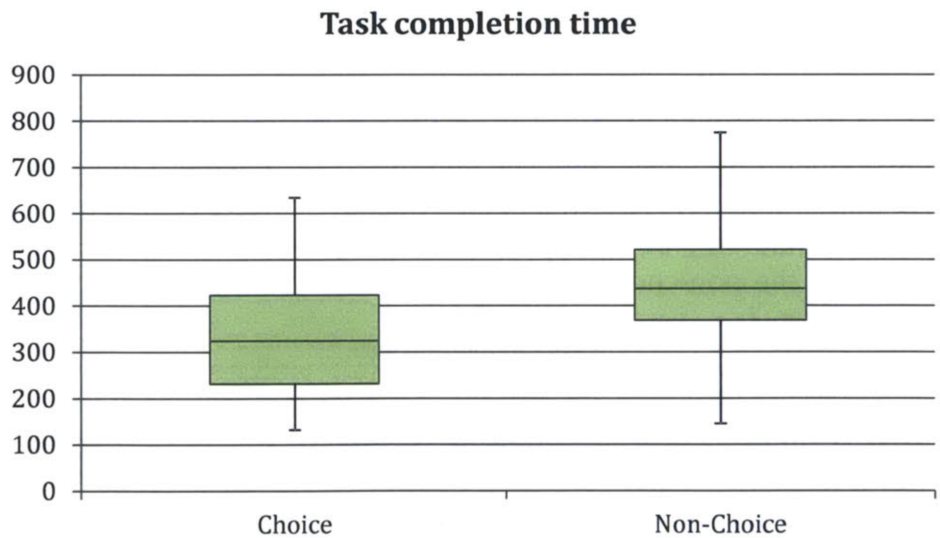
Traveled time in second	860.41	74.99	741.12	91.70	**0.0015**	3.72
Has GPS	0.72	0.46	0.75	0.46	0.9157	0.10
Used GPS	0.90	0.30	0.87	0.35	0.8201	0.23
Age	31.69	14.17	29.11	13.86	0.6921	0.40
Gender (Male)	0.69	0.46	0.73	0.45	0.8742	0.16
Video Game	2.09	1.22	3.25	2.05	0.1292	1.59

Figure 6.8. Overall Average of traveled time in the tour phase - between, Projector and Tablet. (lower the better)

6.6.2 *Measurements During the task phase*

Overview

Overall, the choice group had significantly faster travel times than the non-choice group did (p = 0.0034) as shown in Figure 6.7, while there was no statistically significant difference between the Tablet and Projector group (p = 0.7859) - the Projector group was slightly, but not significantly, faster than Tablet group.
This result suggests that that visual attention division may not be a large factor in engaging in the surroundings to construct a cognitive map, while the induced "in control" mindset may have a greater effect on the engagement level with the environment.



	Choice (n = 30)		**Non-Choice (n = 30)**		**Result**	
	Mean	SD	Mean	SD	*p*-value	*t*-value

Traveled time in sec.	334.0	133.9	446.03	149.28	**0.0034**	3.05

Figure 6.7. Overall Average task completion time - between choice vs. non-choice. (lower the better.

Choice vs. non-choice in each task

We examined independent measures of the users' self-reports of their sense of direction (SOD), gender, and age to validate whether differences in individual conditions affected results. Between the choice group and the non-choice group, there were no significant differences in either category in SOD (p = 0.4195), age (p = 0.8708) and gender (p = 0.1770). The group compositions, then, were fairly homogenous.

	Choice (n = 30)		Non-Choice (n = 30)		Result	
	Mean	SD	Mean	SD	p-value	t-value
Traveled time in sec.	334.0	133.9	446.03	149.28	**0.0034**	3.05
Confusion	11.46	5.77	15.53	6.93	**0.0165**	2.46
Path length	11.68	4.62	13.95	5.41	0.0864	1.74
Rate of task completion	0.94		0.86			

Table 6.6. The result of statistical differences of traveled time, confusion, and path length in choice and non-choice groups.

We measured two dependent variables in the task phase: confusion and length of paths taken between landmarks. The choice group did a better job of finding newer and shorter paths as shown in Table 6.6. The data shows that the choice group was significantly less confused and took a marginally shorter path during the task phase. About 94% of the choice pool of subjects completed their tasks successfully while only 85% of the non-choice pool completed the same task - about 10% of the non-choice group gave up or failed to complete the task as shown in Table 6.7.

Task Completion Rate

	Choice	Non-Choice
Tablet	94.1%	86.2%
Projector	94.4%	85.1%

Table 6.7. Task completion success rate - between choice, non-choice, Projector and Tablet condition. (higher value is better)

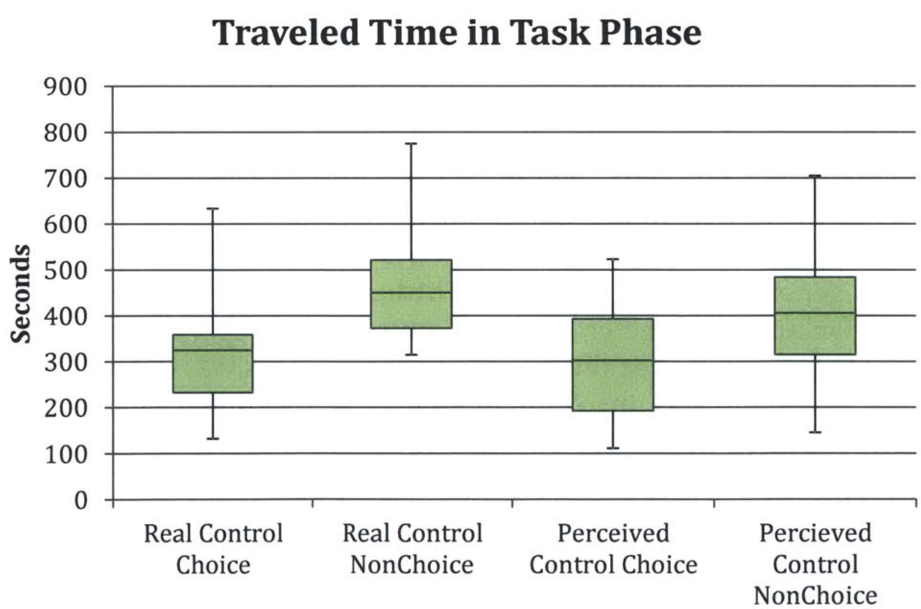
Overall, it is clear that the choice group was better in the task completion rate while the differences between Projector and Tablet groups were insignificant.

6.6.3 Effects of Having Perceived Control

Clearly, providing a route choice made the users more engaged in the surroundings while following the devices. However, we need to identify whether this was the effect of following a different route, or the result of giving the users control over path selection.

To further investigate the route choice effect, we altered the choice group by providing a perceived choice to a third of the users. Each user had to pick which route they wanted to take, but we described the same path in two different ways (e.g. "you can select a path that goes by the amphitheater or one that goes by the Teapot lecture hall). Regardless of the users' choice, we followed the same path and passed through both the Teapot lecture hall and the amphitheater.
The difference from the previous part of the experiment is that under the perceived control condition, users were shown two different descriptions (visual or audio) of the same pathway.

Overall, as shown in the graphs (see Figure 6.8), the two conditions, *Real control* and *Perceived control,* actually had the same effects on the task performance, i.e. finding landmarks faster in choice condition. One thing to note is that the results of the perceived choice group had little differences from the real choice group. This result implies that route choice - even though it didn't make any difference in the end result - actually changed the subjects' mindset and made them more engaged in the task domain.



	Choice		Non-choice		Result	
	Mean	SD	Mean	SD	*p*-value	*t*-value
Actual control	333.3 (n = 20)	124.0	465.1 (n = 20)	124.5	**0.0018**	3.35

Perceived control	309.5 (n = 10)	111.2	427.1 (n = 10)	135.4	**0.0474**	2.12

Figure 6.8. Average task completion time - between real-choice group (left graph) & perceived control group (right graph).

Ultimately, the perception of choice or the act of making the choice caused improved performance in the navigation task, regardless of the actual routes traveled. This suggests that indeed users take more care to be aware of their surroundings when offered a choice.

6.6.4 *Self-report after the task*

After the tour, we measured the subjects' satisfaction with the tour in our survey and most of the subjects were satisfied with the tour. Overall, there were not many differences between the groups, but in the Projector group, there was slightly more satisfaction, perhaps because Projector is less demanding on the users' eyes.

User Satisfaction

	Choice	Non-Choice
Projector	5.89 (SD = 0.93)	6 (SD = 0.57)
Tablet	5.91 (SD = 1.05)	5.81 (SD = 1.16)

Table 6.8. Self-report on satisfaction. between choice, non-choice, Projector and Tablet condition. Scale from 1-Not at all to 7-Very much. (higher value is better)

6.6.5 Further observation

After conducting our tours, we informally interviewed the subjects about the tour, using the devices, and making choices.

Users in general started the tour a little self-conscious because the idea of following an arrow on the ground was unusual. Also, everyone else could see the same arrow, which makes the directions shared. This was useful for tour groups because everyone was involved in following the directions. However, some subjects who used the device individually felt somewhat uncomfortable because such personal information was publicized to everyone around. But as the tour progressed, users said the idea grew on them and using Projector became more natural.

One novel feature of our devices was giving the user a choice in route choosing. Most users felt this route choosing was natural and non-obstructive. Projector users seemed to be more comfortable with the route choice option since the Tablet gave excessive information about the routes whereas Projector gave simple and easy-to-follow instructions. Also, the Tablet users sometimes had trouble hearing the audio cues from the Tablet, distracting from the tour.

We also had some trouble implementing the actual projector idea. The projector we used was somewhat heavy and constantly vibrating, which users found to be distracting during the tour. Also, the projector was not bright enough to accommodate a building with ample natural lighting.

Minor details aside, however, most users did not mind using the devices for the tour. People sometimes inquired whether these applications would be available for the public soon, another indication that they enjoyed using the devices.

6.7 Conclusion of Evaluation

From our study, in comparing the screen-based and projection-based AR interfaces of the navigational systems, projection-based AR interfaces offer a more natural form of navigation. Projector users looked more at their environment and less at the device, resulting in fewer missed turns and fewer wrong turns during the tour. It clearly shows that there was less visual attention division in using the projection-based AR interface. However, there was no indication that users were more engaged in the environment, since there was no significant difference in route retention between the two interfaces.

On the other hand, examining physical and psychological effects on engagement and acquisition of spatial knowledge, we have seen significant psychological effects of perceived control. In allowing users to choose their routes, users were more engaged in their surroundings, and hence performed better in finding landmarks without aid.

Here, though we have concluded that inducing perceived control engages the users more in the task domain, i.e., surroundings of paths, we cannot conclude that any random choices, such as choosing arrow colors, will engage the users more. The path selection process is relevant to spatial knowledge, and as a result, people might have done better in the task phase from this additional information of the surroundings.

7 Conclusion

In this dissertation, we explored the challenges of designing and developing indoor navigation systems. In paticular, we focused on designing Guiding Light, which uses projector based augmented reality, developing and engineering an indoor positioning system for navigation assistance systems, and examining the relationship between visual attention division and engagement level.

First, we have demonstrated how a projector based AR can be used in pedestrian navigation systems by developing Guiding Light with four design iterations. Navigation tasks involve following paths in the real world as well as investigating nearby points of interest. Guiding Light supports projection AR which interacts with objects in the real world to enhance our understanding of the places we visit. We designed the user interface based on the concept of crossing the abstract world and the concrete world that we encounter in everyday tasks. This concept provides the basis for developing various versions of Guiding Light with different combinations of technology to identify advantages and disadvantages of using it in different scenarios. We examined the strengths and weaknesses of using IR LED based interaction, camera vision technology, and tilt & motion sensors, all of which enable Guiding Light to interact with world. We demonstrated that the device with tilt and motion sensors combined with our novel positioning system is sufficient to conduct tasks in indoor navigation, and compared it to using computer vision with a camera. The support of our indoor positioning system reduces the requirement of tracking locations and direction using a camera.

The indoor positioning system is the core and the foundation of Guiding Light in that it enables the system to track location and direction of a user in order to provide timely guidance. Developing such a system was a big challenge for us and we invested more than half of our effort developing it. While most positioning systems only provide location and derive direction from movement, we demonstrated with our novel system that it can provide both position and direction using the same technology. We also demonstrated that our magnetic field based positioning system could provide accuracy within a meter 88% of the time, and a directional error of 4 degrees on average. Although this technology required building new sensors that implement four magnetic sensors, it does not require any additional infrastructure as it uses indoor ambient magnetic fields. This is another advantage of reducing the cost of installation and maintenance of additional devices over other positioning systems that needs infrastructure. In addition, we concluded from our experiment that the magnetic field does not change over time in an indoor environment, so when we construct a magnetic fingerprint map, it will not change over time. All in all, this new technology opens a new area in the field of positioning.

Another important goal of our system is to help users to be more engaged in the task at hand and to alleviate the problems of distraction and disengagement when using navigational assistant systems. We created our design keeping in mind two separate domains: physical constraints and psychological constraints. In the former case we tried to address how visual attention division can degrade engagement in our surroundings by developing projection-based navigation systems. In the latter case we considered the theory of mindfulness and mindlessness. In our evaluation of the system, we compared our system to screen based guidance systems. We also compared two conditions, one that lets users have control of route choices and another that does not have choice option of routes.

We found that projector based AR is effective in navigation tasks in terms of speed of navigation and dealing with obstacles in paths. Orientation of the heads of users in the Guiding Light group showed that their heads were more focused on the environment while users of screen based system looked down towards the handheld screen. The Guiding Light group was less confused and made fewer mistakes in the navigation task. In the latter case of the in-control group versus not in-control group in selecting paths, we found that the group in control of their path had superior results in the engagement of the travelers with passing by surroundings. However, there was no significant difference between screen and projector based AR. This suggests that freeing users from the distraction of a screen may not necessarily make users more engaged in the space. Thus the idea of increasing spatial knowledge acquisition by increasing screen size or providing image landmarks as guidance should be re-evaluated - our study suggests that it may not. On the other hand, a simple intervention of occasionally letting travelers have made a choice between paths shows a significant increase of spatial knowledge acquisition. Subjects who could make choices showed superior performance in finding locations that they have visited before in our experiment, even if it is only a perceived choice. This result may be applied to in-car navigation systems and other systems that give instructions to a user to achieve certain goals.

Future work

There are a couple of further developments that may enhance our positioning system. First, the particle filter employed by our system to eliminate outliers was optimized for corridor environments. In order for the positioning system to be available for general indoor location tracking, our particle filter needs to be implemented with a motion model to effectively control particles in the user's moving direction. The motion model may need to detect two states, moving or stopping, and the moving direction and speed (or velocity) of the sensor. . This could will produce better accuracy of the system in a two dimensional surface. Second, we could use WLAN as a secondary resource for positioning information. The MagCells could be indexed with WLAN's RSSI. This would help reduce the search space of the location of the MagCell. As the size of the magnetic fingerprint map grows, the particle filter may slow down. In addition to the benefits of using WLAN RSSI as the MagCell index, WLAN can be also used to detect local minima detection problems in our particle filter. Because the WLAN's position error does not exceed 21 m (in Media-Lab buildings), the distance between the predicted location by particle filter and the WLAN based location can show whether the particle filter is producing local minima.

In order for indoor navigation assistance systems to be used widely, indoor maps need to be gathered systematically and various ways of collecting map data need to be considered. The government or a company may not be able to single-handedly produce a comprehensive indoor map of the US or even a small city. However, crowdsourcing is one viable alternative for collecting data. Local residents may contribute since they often have more knowledge about the buildings and pathways that they often see and take. For instance, the pathway between the Kendall T stop and the Media-Lab is connected via the MIT Medical building (during the daytime). This knowledge is hard to find in both Google Maps [5] and the MIT Map[6]. Traveling to the student center requires walking through several buildings in and out alternatively, but the internal MIT map does not provide this information. Indoor maps are generally hard to find in both public and private map systems. Mapping the indoor environment is a step towards real ubiquitous computing, and the work of mapping indoor requires broader support in both tools and systems.

[5] http://maps.google.com
[6] http://whereis.mit.edu

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