

Path-Guided Indoor Navigation for the Visually Impaired Using Minimal Building Retrofitting

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ABSTRACT

One of the common problems faced by visually impaired people is of independent path-based mobility in an unfamiliar indoor environment. Existing systems do not provide active guidance or are bulky, expensive and hence are not socially apt. In this paper, we present the design of an omnipresent cellphone based active indoor wayfinding system for the visually impaired. Our system provides step-by-step directions to the destination from any location in the building using minimal additional infrastructure. The carefully calibrated audio, vibration instructions and the small wearable device helps the user to navigate efficiently and unobtrusively. Results from a formative study with five visually impaired individuals informed the design of the system. We then deployed the system in a building and field tested it with ten visually impaired users. The comparison of the quantitative and qualitative results demonstrated that the system is useful and usable, but can still be improved.

Categories and Subject Descriptors: K.4.2 [Computers and Society]: Social Issues - Assistive technologies for persons with disabilities

Keywords: Visual Impairment; Indoor Navigation

1. INTRODUCTION

Navigation and wayfinding to reach a desired destination is a considerable challenge for a visually impaired person particularly in an unknown indoor environment [14]. Path finding is a composition of several cognitive processes like map building, landmark identification, obstacle avoidance and interaction with by-standers to ask directions [25, 26]. Most of the globally present signages are vision based and are inaccessible to them. Locating an accessible signage (tactile, audio) again poses a problem. Navigators currently rely on sporadic help from bystanders and use path integration to follow a given direction [25]. This causes anxiety, embarrassment and makes them reluctant to go alone in an unfamiliar building [15]. This was also corroborated in our own formative study.

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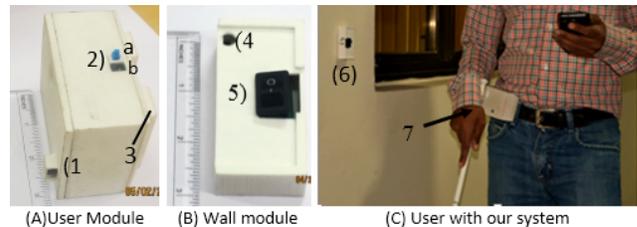


Figure 1: System prototypes. (1)IR receiver, (2a)tactile push button switch for operation, (2b)charging port and (3)belt fix, (4)IR transmitter and (5)switch, (6)wall module retrofitted in the building, (7)user module.

Existing commercial navigation systems based on GPS (eg. StreetTalk [3], Sendero [1]) have made navigation a lot easier in outdoor environments. But their major shortcoming is that they can only identify very specific landmarks encountered by the user and typically do not work indoors. Several attempts have been made to address the problem of indoor navigation for the visually impaired. However, no single solution has found wide acceptability and long term deployment for use. Most of the systems present today are either only landmark identification systems with no path-based guidance (eg. RFID [22, 13], infrared based systems [5, 32, 34]) or are inaccurate for an indoor environment (eg. dead-reckoning [17, 12, 36], Wifi [28, 31]). Few systems exist which are both omnipresent (which could localize the user accurately from any point in the building) and provide step-by-step path based wayfinding (eg. Building Navigator [18], Andha Astra [33]). These systems are bulky to carry [10] or expensive to operate [29].

In this work, we present the design and implementation of a portable and self-contained indoor navigation system which is currently deployed in a university building. Comprising of a network of wall mounted units and a user module coupled with a mobile application (Figure 1), the system downloads the map of the building, localizes the user within the building, takes the destination as input from the user, and then helps him to independently navigate to his destination using step-by-step navigational instructions. Novel features of the system are:

- Path-based navigation with active guidance for turns and *important landmarks* in the course of travel.
- Update on *position awareness* information particularly *obstacle warning instructions*.
- Update on *position correction* information in case the user deviates from the path.
- Use of *minimal additional building augmentation* while providing good accuracy.

- *Small, compact design* of user module and hence convenient to carry.

These features make the system a socially apt and efficient indoor navigation guide, thereby reducing anxiety and embarrassment in public places.

Further, we present the results and insights from a before-and-after study in which a group of 10 users participated to validate the usefulness and usability of the system and gather insights for improvements.

2. RELATED WORK

Most of the proposed wayfinding systems for visually impaired are outdoor systems which mainly use GPS for localization purposes [24, 32]. Indoor systems cannot use GPS signals, as buildings block them. To surpass this issue, researches have developed alternative localization techniques that can be distinguished into two different categories [10].

Dead-Reckoning techniques estimate the user’s current localization based on a previously estimated or known location. While the user is moving, dead reckoning estimates the user’s location by interpreting readings from one or more sensors that the user carries such as accelerometers, magnetometers, and gyroscopes [12, 17, 21]. The initial location is typically determined using GPS [17], RFID tags [21], or cellular phone positioning [30]. One significant benefit of this approach is the low installation cost, as it does not require physical infrastructure. The main drawback of this technique is the error accumulation over time as dead reckoning is a recursive process and each sensor has some inaccuracy.

Beacon-based approaches augment the physical space with identifiers. Such beacons can be retro-reflective digital signs detected by a camera [7, 35], infrared [5, 32, 34], RF [9], RFID tags [22, 13, 8], or ultra-sound identifiers [29]. Locating identifiers may be hard, as beacons may require line of sight or close proximity to the human. This significantly delays the user and makes him embarrassed. Other beacon-based techniques use triangulation to locate the user. For example, wireless network positioning systems [28, 31, 23] may triangulate the location of base stations using the provided signal strength or could be building signal strength maps. Wireless nodes however, often suffer from multi-path effects or interference.

The system most similar to ours is a commercial product called Talking Signs [5]. It uses a network of infrared transmitters installed on the walls or poles at tactical locations. Despite the low-cost of the IR technology, it suffers from the same limitation as other beacon-based approaches. A lot of IR modules have to be installed for precise localization and the system cannot provide path-based navigational directions. This increases cognitive load on a visually impaired user and is hazardous in case of any deviation or mistake.

Beacons are often integrated with dead-reckoning to correct the accumulated error through environmental knowledge [17], RFID tags [21], ultrasound beacons [20], and map-matching [21, 27]. Our system builds upon the beacon based Talking Signs system [5] by using infrared sensor installation at turns and important landmarks in the building to localize the user when he is near them and; augments it with selective dead-reckoning by using only the accelerometer to calculate the position in between any two infrared sensors. Thus it is omnipresent, provides step-by-step path

based guidance and topological information of the surroundings, obstacle warning instructions and corrective directions when the user gets deviated. The dead-reckoning technique significantly reduces the number of IR beacons and hence the overall system cost. Further, the system is convenient to carry, easy to learn and operate, not easily visible and can be easily mounted on existing building infrastructure.

3. SYSTEM OVERVIEW

We describe the design process using a formative study with the visually impaired persons before providing the technical description and implementation details of the system.

3.1 Design Process

We conducted a formative study to gain insights into the process of indoor wayfinding and arrive at desired specification for the proposed system. Five people (3 males and 2 females) from Delhi were recruited; ages 21-35 years, varied onset of blindness from birth to legally blind for 3 years, and varying level of blindness from partial vision to fully blind. All the participants were accessible mobile phone users with screen readers installed in them. They mostly used canes and would take help from sighted persons for finding their path since no indoor wayfinding system exist in India.

The task: Participants were asked to navigate a predefined track in two places unfamiliar to them: a 90m track in an uncrowded academic building and a 120m track in a busy shopping mall in Delhi. We assigned a common destination to each user and asked them to take their usual approach to find their way to the destination. We saw that they usually try to find signs, ask for help or resort to ad hoc approaches. The main issues observed during navigation were confusion regarding the correctness of their current course, absence of bystanders in some areas, language barriers in asking for help, unhelpful and aggressive bystanders in some cases, vulnerability to injuries during navigation and lack of confirmation upon reaching the destination.

The interview: After the study, we interviewed the participants to discuss the problems faced during independent indoor navigation in general and compiled their views for an effective technological solution. The interviews emphasized their high degree of anxiety in accessing unfamiliar locations independently. Their requirement for sighted assistance in general induces inertia towards going anywhere alone. They are frequently subjected to gaze and unwanted attention from the surrounding people. Some participants also reported getting lost and injured in cases at times.

All the participants emphasized the need and utility of an affordable navigation guide to travel independently. The key requirements articulated by the participants included:

- Audio-based guidance system which would give information about the *current location, impending turns and important landmarks to the destination* and approximate distance of each section between the turns.
- Warning about *impending obstacles* in the path of travel.
- Audio feedback to *confirm the arrival of the destination*.
- Preferably, *utilize a device an individual may already own* and be comfortable with operating the same.

These insights informed the design of our system which is presented in the following sections.

3.2 System Design

The system consists of the two major components: (1) wall modules deployed in building and, (2) user end comprising of a waist-worn device coupled with a mobile phone.

Building: The system consists of network of infrared based wall units retrofitted at specific locations in the building. We chose to use IR technology for locating the user as they are extremely accurate and inexpensive [11]. These sensors transmit the unique IR tags corresponding to their location perpendicular to the direction of motion of the user.

User end: The user end consists of two modules, a mobile phone and a user module.

Mobile phone: A primary goal of the work was to employ a device already owned by the user. Thus, we chose to use a mobile phone which is commonly used by people [16]. Furthermore, applications on new smart phones offer many functionalities and services including accessibility features like screen readers and vibration alerts.

User module: To receive the IR signal transmitted from the wall modules, we have develop a custom user module since modern day mobile phones do not have infrared components. Also, to enhance the accuracy of the system and to substantially reduce the number of wall mounted units, we decided to use the accelerometer used in high precision pedometers. It returns the number of steps traveled by the user which, when multiplied by the average step length, gives the distance traveled. The average step length is user configurable on the basis of his height. Since an accelerometer has to be worn close to the legs of the user to calculate steps, we decided to put the module near the waist. Putting the module on legs gives better accuracy but that may be inconvenient for the user. The module connects with the mobile phone over bluetooth. System prototypes are shown in Figure 1.

To provide an estimate of the number of wall units reduced by the use of accelerometer, consider the following: The maximum localization error of the system is $\pm 1.6m$ calculated via separate experiments. This accuracy is provided by a network of infrared modules situated at an interval of 3m. The use of accelerometer gives the same accuracy and path-guidance, but with increased interval between the infrared modules of 8-10m! Details on localization experiments are beyond the scope of this paper.

User interface: All the information is conveyed to the user via the Text-to-Speech (TTS) engine of the mobile application, and also displayed in a large font size to provide for someone with partial vision. Vibration alerts are used to provide continuous feedback for being on the right track.

Figure 2 shows sample screens from the mobile application interface. The text on top shows the audio message when the particular screen is activated. The screen on the right is displayed when the user is moving. The screen is divided into at most two parts so it is convenient for visually impaired person to touch and operate. Within a screen, the relative sizes of the buttons are kept according to the need. E.g., in the rightmost screen, chances are more that the user would press the ‘more information’ button to get the navigational instructions for travel and hence, the ‘cancel travel’ button is kept small. We also have a qwerty keypad based phone implementation (not shown). The texts at the bottom are example audio messages during navigation.

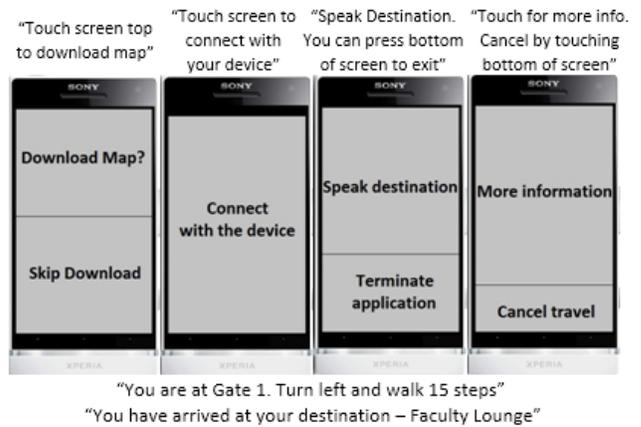


Figure 2: Sample screens from the mobile application.

Maps: The building map consists of a topological map with metric information between the waypoints, annotated with additional information about the path like obstacles. An example map file converted from a L shaped path is shown in the Figure 3. In each line, the first block represents the landmark and the other blocks represent its neighbors. Within each block, the string is the name of the landmark followed by x-coord, y-coord and the floor number.

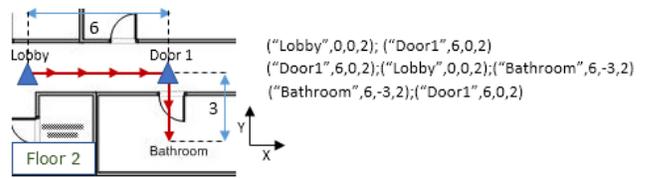


Figure 3: An example map file converted from floor plan of a building. Red arrowed path is the navigational track.

3.3 System Usage

The basic process to use the system is shown in Figure 4. The user downloads the map of the particular building from our server. He chooses from the list of building maps stored on our server and the selected map gets downloaded in about 2 sec. He then connects the mobile application to the user module using the touch screen. After a successful connection, the user has an option of either speaking his desired destination or typing the destination using the QWERTY keypad. If a close match with a location in our database is found, the main process of the application begins.

As the user walks, the mobile application receives the current position and the number of steps data from the user module and dynamically calculates the path to the destination using the shortest path algorithm. The user is kept

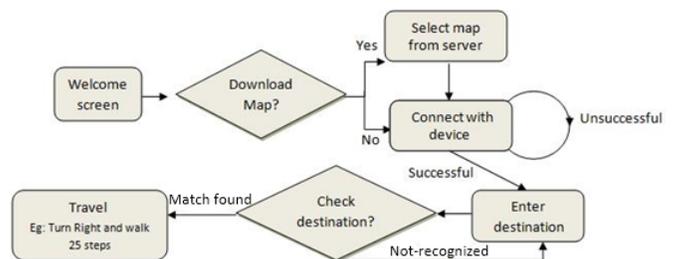


Figure 4: Flowchart of the mobile application explaining the surface working of the device.

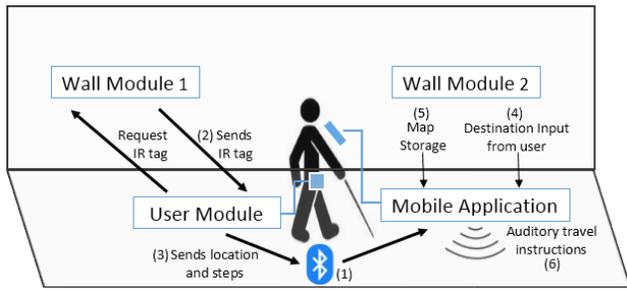


Figure 5: Background operation of the system.

informed about his current location and navigational directions to the next waypoint in the path of travel (viz. intersection, lift, destination etc.). The navigational directions include any turn to take and the number of steps to travel. Also, a warning is given if the user takes a wrong turn or deviates from the path, and the path is re-calculated from the user’s current location to his destination.

3.4 System implementation

An example overview of the system is shown in Figure 5. (1) The mobile application connects to the user module through Bluetooth; (2) The wall module when requested by the user module, transmits the location specific tag. (3) IR location information and steps from the accelerometer are transferred to the mobile application. (4) The user inputs the destination to the mobile application which calculates the path of travel from the stored building map (5) and the information received from the user module (3). (6) The application then conveys the navigational directions to the user.

User module: The user module consists of an Atmega328 microcontroller, a serial RN-41 bluetooth module, a 3-axis accelerometer (ADXL345), two ST-12 IR Codec chip from Sunrom technologies [4], IR transmitter and receiver (TSOP 1738) and two Ultralife UBP001 Li-ion batteries (each 3.7 V, 900mAh) connected in series. The battery life is approx. 14 hours with the full charging time of 6-7 hours. When the battery is low, the module sends the “BATTERY LOW” signal to the mobile application through Bluetooth which informs the user. The two ST-12 IR Codec chips act as encoder and decoder for transmitting and receiving data respectively. Projected cost of the fully customized user module is < \$20.

Wall module: The wall module consists of Microchip’s PIC18LF4550 microcontroller with two ST-12 IR Codec chips for encoding and decoding, IR transmitter and receiver (TSOP 1738), 9V battery from Duracell and a magnetic buzzer (Piezo buzzer - B20). The PIC microcontroller runs on nano-watt technology to save power. The tag of the wall module is saved in EEPROM of the PIC microcontroller. The microcontroller operates in sleep mode to save power and wakes through the interrupt from user module to transmit data. As explained in Section 6.1, the buzzer is an add-on feature to help the user identify the exact location of his destination. A single 9V Duracell battery can run the module for 2-2.5 years with continuous operation. Cost of setup per floor in a typical building (20 wall modules) is \$200.

Mobile application: The mobile application is built for Google Android based platforms. The application uses *Text-to-Speech (TTS)* API of Android to give auditory output in English language to the users. We have used *Amarino*

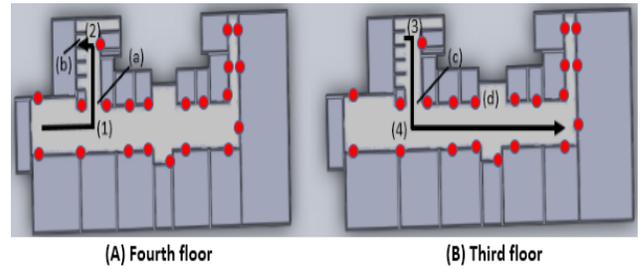


Figure 6: Track used for user trials. Starting point is on floor 4, end point is on floor 3. The dots represent the position of wall units and black arrows show the traversed path. 1,2,3 and 4 represent four turns in the path; door (a), lift (b), door (c) and wide corridor (d) are annotations. Total length of the path is 75m.

toolkit for bluetooth communication with the user module. The application uses our map file to find the shortest path to the destination using the Dijkstra’s algorithm. Users can enter the destination via the QWERTY keypad and the application auto-completes the entered string if there is only one possible match. For Android phones with OS version 2.3 or above, the speech recognition feature can also be used to identify the location speech input using Google *RecognizerIntent* API but since it is rather inaccurate in interpreting regional accents, the recognized strings are further matched with our database of locations in the building.

Building maps: The floor plans of the buildings are available in the DWG format with the building authorities. With the help of any floor plan viewing software like AUTOCAD, the specific locations of the wall modules can be marked. This DWG file is then converted to coordinate format (x,y,z) in the form of a text file which forms our map file. After this one-time task, the map is uploaded to a central server from where the file can be downloaded to the user phones.

4. USER EVALUATION

4.1 Study Design

Goal: The goal of the study was to determine the efficacy of the system for enabling persons with visual impairment in the age group of 18-40 years to independently navigate in indoor environments with narrow corridors.

Experimental setup: The system was installed in 4 floors of a university building. A total of 84 wall modules (21 per floor) were deployed at an interval of about 8m (Figure 6). We conducted the user study on the third and fourth floors of the building. The walking corridor was tiled, which facilitated quantitative estimation of deviations from the path.

Participants: The study participants included 5 males and 5 females selected randomly from two NGOs (Table 1). They had basic English literacy and adequate knowledge of using a mobile phone. Individuals possessing additional impairments like locomotor or hearing problems were excluded from this study. Participants mostly used canes and would typically ask for directions from sighted individuals while navigating. Two participants were somewhat familiar with the building while the rest had no familiarity.

4.2 Methodology

The major phases of the study are outlined in Figure 7.

The user visited the experiment building 6 times over a period of about 12 days (1 visit for baseline study, 3 for train-

Table 1: Characteristics of the participants used for the study.

	User ^a	M/F	Age	Impairment	Onset Age	Familiarity with site	Phone model	Accessible?	O&M Training?
1	Amit	M	30	Full	Birth	Low	Nokia E71	Yes	No
2	Rita	F	32	Partial	Birth	Low	Samsung Pro	No	No
3	Sita	F	17	Full	Birth	Low	Nokia 101	No	No
4	Anu	F	22	Full	2.5yrs	Low	Digibee G225	No	Yes
5	Raju	M	27	Full	Birth	Medium	Huawei U8850	No	Yes
6	Neha	F	25	Full	20yrs	Low	Nokia 112	No	Yes
7	Asha	F	26	Partial	18yrs	Low	Nokia 3310	No	Yes
8	Raj	M	27	Full	Birth	High	Nokia C5	Yes	Yes
9	Anil	M	21	Full	Birth	Low	Nokia N97	Yes	Yes
10	Ali	M	21	Full	2-3yrs	Low	Nokia C5	Yes	No

^aWe replaced the names of the participants to protect their anonymity.



Figure 7: Phases of the study indicating key activities.

ing, 1 for device testing and 1 for Focus Group Discussion). The experiments were conducted in the morning time when people roamed around. The study was scheduled as follows:

Baseline Study: Before introducing the device, we asked the users for problems they face in indoor navigation. Then, they navigated between two predefined locations on the 3rd and 4th floors of the building using their usual navigation methods. For comparative analysis, volunteers gave the same instructions to reach the destination as given by our system except that all of them were given at the beginning once. Also, they could stop navigating midway and raise their hand to ask for directions if they forgot or got confused. In such a case, the volunteer correctly oriented the user from their current position and the navigational directions were repeated. If a major deviation was observed¹, reorientation was done to avoid the anxiety of getting lost.

User Training: User training involved demonstration of the system, testing the understanding by performing basic operations like opening the mobile application, entering possible destinations, wearing and operating the waist module etc. and, volunteer assisted mock navigation with the device on the training tracks containing 21 different locations.

Device Testing: The user performed device assisted navigation on the same track as used for baseline study. Randomization of the path was done by introducing artificial obstacles like boxes and bars in the path. The users had only one prior attempt at navigating on the sufficiently long track during the baseline study and there was a period greater than a week between the two tests (interspersed with periods of training, done at a separate location). The testing concluded with a qualitative interview session (and also a focus group discussion later) in which the users expressed their views on the utility, merits, demerits, ease of learning and further improvements for the device.

Pilot Study: The entire process was first piloted on Amit. During the baseline trial, he significantly deviated from the path and took a lot of time to complete. So, for the subsequent users, additional precautions were introduced like reorienting test subjects after a major deviation.

¹Any deviation greater than 6m is reported as a major deviation.

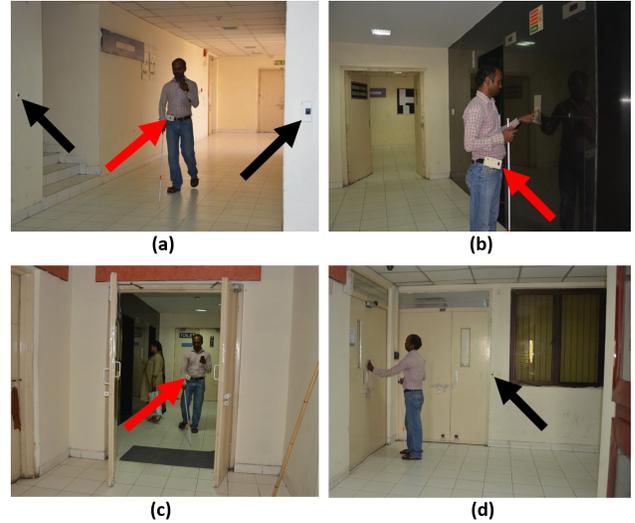


Figure 8: User reaching the destination with the aid of the system. User module (red arrow) and wall module (black-arrow). (a)Start position on floor 4, (b)waiting for lift, (c)entering floor 3, (d)final position.

5. FINDINGS

5.1 Quantitative Results

All users were able to successfully navigate to their destination using our system. Figure 8 shows some examples for one user. Significant improvements were observed in the measured parameters.

Minimal deviation: No major deviations were observed for all the participants in the study during device testing. Comparison of the results for baseline and device testing are shown in Table 2. Our system was able to successfully guide the users around turns and obstacles. However, two users were close to colliding with the half-closed door shown in Figure 8(c), indicating that information about similar structures also needs to be provided. Figure 10 shows how our system instructed the user to walk straight on a wide corridor. The trial with Neha was aborted as she became conscious of five volunteers focusing on her trial.

Reduction in help seeking events: Table 3 shows the reduction in number of times the users asked for navigational directions during device testing. The system was able to effectively guide 7 out of 9 users to the destination without any external sighted help. Sita and Raju were uncomfortable in operating the lift and volunteers had to intervene.

Table 2: Comparison of ‘major deviation from the path’ for baseline and device testing.

	Rita	Sita	Anu	Raju	Raj	Asha	Anil	Ali	Amit	Neha
Without system	1	2	2	3	3	2	2	3	4	3
With system	0	0	0	0	0	0	0	0	0	-

Table 3: Comparison of ‘number of help seeking events’ for baseline and device testing.

	Rita	Sita	Anu	Raju	Raj	Asha	Anil	Ali	Amit	Neha
Without system	3	3	4	6	4	3	2	5	3	4
With system	0	1	0	1	0	0	0	0	0	-

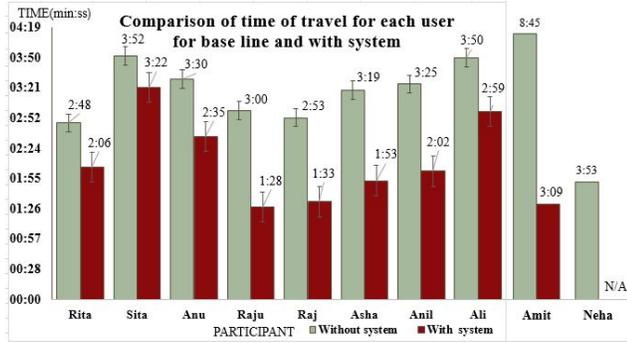


Figure 9: Graph showing the ‘time of travel’ for each user without and with our system. The graph for Amit and Neha is shown separately.

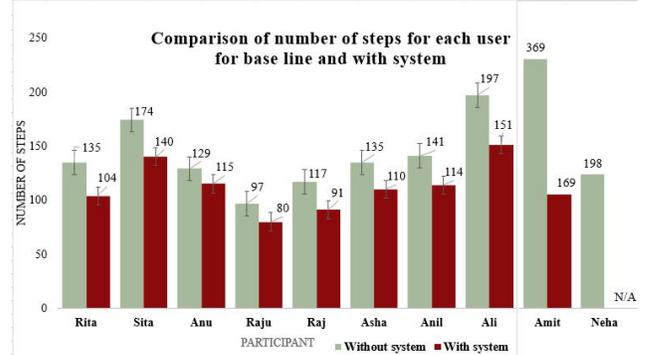


Figure 11: Graph showing the ‘number of steps taken’ by each user without and with our system.



Figure 10: (a) User gets deviated while navigating without the system at position ‘d’, Figure 6. (b) Corrective navigation with the indoor navigation system.

Optimal time of travel: All users were able to reach the destination much faster with our system. Figure 9 plots the time taken by the users to traverse the experimental path during baseline and device testing. The pairwise t-test was significant (*two-tailed* $p < 0.01$). The pilot participant (Amit) was not stopped by the volunteers even after he deviated beyond 6m from the ideal path.

Straight, path-directed motion: The number of steps taken by users reduced during device testing as they followed the accurate instructions of the mobile application and did not depend on exploration of the surroundings (Figure 11). Pairwise t-test yielded *two-tailed* $p < 0.01$.

5.2 Qualitative Analysis

The majority of users expressed that indoor navigation is a day to day problem and they have to resort to a hit and trial approach for finding their way. They understood the usage of the device effectively during training and comfortably reached their destination during device testing.

Easy to wear and operate

Users mentioned that the module was easy to put on, remove and carry. They appreciated the on/off push buttons which allow them to operate the module without braille markers. The charging port was compatible with the Nokia mobile

phones that they commonly use (Table 1). The texture was slightly rough for them but we explained that this was a trial prototype. There were two suggested improvements. First, they advised to reduce the dimensions (and weight) of the module to the size (and weight) of a data-card (approx. 7X3 cm). This would ease the operation further and make it less visible. Second, some users were concerned with the belt attachment. Raju was quoted as saying - “The device should have a hook to attach it easily to any part on the body. Opening and closing of belt in public is very embarrassing and hence, not an option.” A female user Anu expressed: “Women do not always wear jeans. They may wear skirt, sari or salwaar/kamiz (traditional Indian dresses with a long top). So, it is necessary to develop an alternate attachment.” We propose to develop a hook attachment in the future.

Two users forgot to switch-on the user module before the trial. The application successfully prompted them to turn it on. One user forgot to switch-off the user module after the trial leading to power wastage. He suggested that the module should periodically vibrate when on. All users preferred the white color for the module.

Friendly application interface

Users were happy with the carefully designed stages of the mobile application and appreciated its features.

Raj: “Since the literacy rate is quite low in developing countries, the speech input can make the device universal to work with. The application is user-friendly and the touch input is easy to learn.”

Asha: “I have so many options to use the application. I can either listen to audio messages or use the large font to read... or can even use the screen reader to read the text.”

Average time taken to operate all the initial stages of the application was 9.5 sec (best: 7 sec, worst: 16 sec); average time spent in individual stages being 3 sec to download the map, 2.5 sec to connect with the phone and 4 sec to enter the destination. All measurements were done through visual inspection by the volunteers and are approximate.

The users preferred speech over QWERTY over touch-based input whenever there was a choice. They found it easier to directly respond to the application as it was speaking to them, hence speech input was the most preferred. The preference of QWERTY keypad input over touch is evident as all the participants owned non-touch based phones (Table 1) and consequently, it was easier for them to type. The users said that the applications in developing countries should also target non-touch based dumbphones due to low penetration of smartphones among visually impaired population, even in urban areas like Delhi.

We observed problems with speech recognition during the training. Users had different ways of pronunciation as they came from different geographical locations in India. Few uncommon locations required 2-3 repeats for some users having a peculiar accent. The android version we used does not recognize Indian accent.

Guided, clear and audible instructions

Users appreciated that the navigational instructions were accurate and precise to not cause any cognitive overload, yet were detailed enough to create a good mental map of the environment. One contribution of our research is the conveying of selective amounts of two types of navigational information at appropriate times: landmark/topology based (eg. wide corridor, obstacles) and metric based (steps). Landmarks and turns were informed 2-3m before reaching them. To prevent information overload, automatic metric directions were only given at the start and the end of the corridor but users had an option for manually obtaining them anywhere by clicking on the ‘more information’ button (Figure 2). Otherwise there were vibration alerts for continuous confirmation of being on the right path. This balance of pushed and pulled information is another contribution of our research.

Amit: *“The device conveys the navigational instructions accurately and even warns me when I mistakenly take a wrong turn. Initially, I got lost and took a long time to reach the destination. When introduced to the device, I was very optimistic. I gained confidence with the system during training and was able to easily reach the destination.”*

Raj: *“I can’t believe that the system gives me much needed directions on how to operate the lift and open the door. I feel myself efficiently navigating as any other person around...”*

The instructions were clear and audible. Specifically, the speech-rate (120 words/min) and pitch (150 Hz) of the instructions were appropriate for all users both in crowd and solitude. Some users had trouble understanding some TTS words initially during training though they eventually got used to the application. There was no visible interference or confusion when users passed each other during training.

The application also has a user triggered exploration mode where detailed information about the surroundings is given as if one is exploring the place. For example, application would say: “On your left, there is a Saloon... On your right, there is a Nike showroom... Walk straight 55 steps to go to Washroom.” We did not test this feature on our sample population during the controlled trial but when asked during F.G.D., users expressed that this option would be useful for public museums and malls. However, it is possible that too much information could ultimately become annoying [19][37]. We plan to test this in future.

Helpful features like buzzer, map download module

In our earlier studies, after reaching the vicinity of the desired destination, the users used to get confused about the exact location of the door. Thus, we have fitted the destination doors with a special user triggered buzzer module.

Neha: *“Audible Indicator (buzzer on destinations) is a great feature. This helps me not to enter the wrong room or collide with obstacles. Also, pinpointing the location of doors is easier”*

Ali inquired on how would they use the system for multiple buildings if they do not know the building name and hence could not choose the building map from the server. For this, we have developed a lab prototype for a module which shall be installed at the building entrance to transfer the map to the mobile phone via bluetooth. This also informs the user that the building contains our system.

Overall system effectiveness

Users appreciated that the system was easy to learn. Average time for learning the system was about 2.5 hrs over a span of 3 days (training stage 1: 11.2 min, 2: 23 min, 3: 112 min). Total learning time for each user is shown in Table 4. Users found our training protocol to be effective (Likert scale responses: M=4.5/5, SD=0.5) but suggested the requirement of a self-training manual for remote areas.

The anxiety of the users decreased while navigating with the aid of the system as shown in Table 4. Average confidence level on Likert scale responses was 2.3/5 (SD=0.9) for baseline and 4.2/5 (SD=0.8) for navigating with the system.

The system did not attract unwanted attention from people. There was no visible interference from by-standers during navigation. Volunteers reported that some people were even unaware of the blind user navigating close-by.

During F.G.D., 9 out of 10 users expressed their intention to buy the module for \$20 if the improvements were incorporated. The mean overall satisfaction with the product was 3.6/5 (SD=1.1). One user who gave the low rating (2/5) wanted to reevaluate after the improvements.

6. DISCUSSION AND FUTURE WORK

Impact of not using the primary mobile phone: We have developed the application only for android phones and none of the users had an Android based mobile phone. The users operated the phones provided by us. This might have led to an increase in the training time. However, to have a more reliable estimate of the system learning time, we also did the first and second stages of training with an additional android phone user - Atul. He was able to learn the usage of the application relatively faster than others. However, we can not generalize the results with only one sample. Due to time constraints, Atul could not come for the entire trial.

Line-of-sight requirement: Our system uses line-of-sight communication between the user module and the wall modules. Though our IR signal is strong enough to pass through a thin cloth and has a wide receiving beam angle of about 35°, this could still pose a problem in crowded places and in cases where user is wearing a long thick top. However, we did not observe any IR signal misses during our trials. Also, infrequent IR misses are unlikely to cause system failure.

Building infrastructure requirement: Though we have substantially reduced the number of wall modules as compared to other beacon based approaches, our system still

Table 4: Total learning time (min) and comparison of the confidence level for baseline and device testing.

Parameter	Rita	Sita	Anu	Raju	Raj	Asha	Anil	Ali	Amit	Neha
Confidence w/o system	3	1	2	4	3	3	2	1	2	2
Approx. learning time	155	225	150	90	90	130	150	170	170	130
Confidence with system	4	3	5	5	5	5	3	4	4	-

requires installation of about 20 modules per floor in a typical public building. We propose to augment more dead-reckoning sensors like gyroscopes and compasses in future (eg. [10]) to further decrease the wall units to the extent of 1 or 2 per building floor while still providing path-based guidance. Further, use of small solar charging batteries which can be charged indoors (eg. [2]) would eliminate the need for replacing the batteries of wall units. These steps would reduce system maintenance and increase scalability.

Unideal bystanders: Our strategy of asking the user to raise his hand in case he feels discomfort during the trials and only then giving him directions for the path ahead, is not an idealistic portrayal of the real world situation wherein the user can ask for instructions from the bystanders only when they are present and if they are present in large numbers, as and when he wants.

Managing permissions for downloading maps: This is outside the scope of the present work and we hope to address this in future. Also, technology for creating 3D models from programs like Sketchup (eg. [10]) would make the system more scalable. The anticipation is that it will be possible to have community-based efforts for the annotation of large scale module creation for public spaces such as airports, museums, railway stations etc.

7. CONCLUSIONS

We reported the user-centric design and evaluation of a novel system which when deployed can help the blind users to effectively navigate in indoor environments. It uses minimal building retrofitting, provides step-by-step path based guidance and is socially apt. The system can also be used by people with cognitive disabilities and sighted people. Due to its low-cost implementation (< \$20 per user module, \$200 per building floor), this contribution will be particularly important in low-income regions, as well as in developing countries where about 90% of the blind people reside [6].

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