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Inclusive Framework for Indoor Accessibility in Low Resource Settings for Persons with Visual Disability

Vikas Upadhyay and M. Balakrishnan
Amarnath and Shashi Khosla School of Information Technology,
Indian Institute of Technology Delhi, New Delhi, India
vikas.upadhyay@cse.iitd.ac.in, mbala@cse.iitd.ac.in

Abstract

The rising adoption of mobile technology in low resource countries like India has contributed significantly towards independent outdoor accessibility for all including persons with visual impairment (PVIs) through applications such as Google Maps, Lazarillo, Blind-Square, and Soundscape, etc. In contrast to this, indoor accessibility is challenging for PVIs, mainly due to the uneven landscape of indoor maps with accessibility information, as well as accessible mediums to communicate them. This makes them continue to feel more dependent, less confident, and more insecure. The major contribution of this paper is to address the problem of indoor wayfinding and accessibility for PVIs to a certain extent. This work involved an eighteen-month-long system-level development including need assessment, design, implementation, and testing. The proposed system includes a custom web-based indoor mapping tool to create digital indoor maps and, an indoor accessibility application for the PVIs. We investigated the requirements and feasibility of indoor wayfinding and accessibility information in the context of low-resource countries. We deployed this system into three distinct venues including a hospital covering a total mapped indoor area of about 40000 square meters. Initial user feedback has clearly shown that the indoor maps and accessibility information have the potential for a significant improvement in indoor navigation and accessibility of these spaces with a low-cost intervention. Based on these understandings, we propose a step-by-step procedure to set up a digital map and localization infrastructure for indoor spaces and build accessibility applications around that. Our iterative implementation has proven to be an easy-to-scale mechanism in similar indoor spaces.

Keywords

Indoor Mapping, Accessibility, Navigation, Wayfinding, Location-Based Services, Visually Impaired

Introduction

Out of a total of 285 million populations, approximately 91 million people with vision impairment are living in South-East Asia (Furtado et al., 2020). Most of these populations (Approximately 90%) are dependent on sighted assistance for any activities that require indoor mobility. Independent indoor mobility poses considerable challenges for PVIs and limits their opportunities in life to access education, job, entertainment, and social engagement which make them feel isolated (Chanana, 2020). Globally, the landscape of accessible indoor maps and mediums to communicate wayfinding and accessibility information are extremely poor. This is mainly because indoor navigation and accessibility are still not a commodity and typically require customization at considerable costs and the existing solutions are highly customized for a specific environment whereas there is no widely accepted solution exists. In a low-resource setting, standard solutions like “clear” signage that can at least support the PVIs with sighted assistance, are either missing altogether or not effective with very few exceptions of airports and modern metro stations (Ahmed, 2015). Further, as they do not get easily updated when major structural changes happen, they can also be very expensive to maintain. Accessibility of signage and other wayfinding cues for PVIs is still a challenge, globally. The revolution of outdoor navigation over the last decade has shown, that low-resource countries have bypassed the use of physical maps in outdoor navigation tasks and are extensively using digital maps. To appreciate this difference, we should understand that two key technologies that have revolutionized outdoor navigation - satellite signals to support GPS on mobile phones as well as satellite (or other forms of aerial) imaging for mapping public spaces are not available for indoor spaces at scale. This has also been hindered by the non-emergence of global standards for indoor navigation and accessibility. Thus by and large solutions that have been developed for PVIs are generally customized, do not scale well, and are completely unaffordable for public spaces in low-resource countries (Simões et al., 2020). This work is primarily meant to address this gap. To understand the challenges related to indoor wayfinding and accessibility, we investigated a range of public indoor spaces that included a tertiary hospital, an academic institution, and a national center for visual disability. We found that wayfinding and accessibility are challenging in most of these spaces primarily due to the limited wayfinding and accessibility information as well as the medium to communicate them. We also identified other concerns emanating from limited access to physical, functional, and accessibility information in a public facility. We firmly believe that any successful solution that has the potential to scale in a low resource setting has to address the following four key broad issues.

- It should require only inexpensive infrastructure enhancement
- Creating information to support wayfinding and accessibility must be possible with low skill set employees without requiring access to original drawings of the building
- The solution should support public functions provided by the building
- Support the vast diversity of users including local language support

In this paper, we presented a novel indoor mapping framework to create and update information and map data APIs to build applications around this. To make the solution relevant to low-resource settings, we explore systems requiring low capital costs and even lower service and maintenance costs. "*Major contributions of this paper include, (i) An assessment of indoor wayfinding and accessibility needs for PVIs. (ii) IncluMap: A framework to create, and update accessible digital maps with wayfinding and accessibility information, (iii) IncluNav: An inclusive interface to access map information for indoor navigation and accessibility, (iv) Navigation system deployment at three distinct places to evaluate implementation requirements* *and feasibility in a low-resource setting (v) An open standard operating procedure to create indoor maps and accessibility information to share over IncluNav or build custom applications."*

Earlier Work and Limitations

Earlier studies have suggested solutions to support wayfinding including – sequential mapping (Guerreiro et al., 2017), localization (Ahmetovic et al., 2017), path planning (Kalia et al., 2010), strategic inclusion of signage (Greenroyd et al., 2018), modeling of indoor facilities. Furthermore, there are insights available on open spaces journey planning and engagement for PVIs (Bandukda et al., 2020). In the context to low resource setting, many PVIs mention that taking help from sighted assistance is also challenging many of the public buildings don't have clear wayfinding signage also reported in earlier studies (Ahmed, 2015). Apart from the cost of retrofitting all existing buildings, maintaining consistency due to incremental design changes is also a challenge (Upadhyay et al., 2019). Even the available signage is inaccessible due to a variety of reasons - illiteracy or low education levels, low vision, and unfamiliar language(Gupta, 2008). The problem related to inclusive and accessible mapping has been highlighted (Froehlich et al., 2019) but there is very limited research available that understand and address the indoor accessibility issues in low resource setting (Barbareschi et al., 2021). For example, in a low-resource setting, there may be multiple uses of the same space for different functions at different times, this transient information creates confusion hence to improve accessibility this also needs to be captured and delivered to all including PVIs (Upadhyay and Balakrishnan, 2021a).

Besides creating indoor maps and accessibility information, indoor positioning is another important requirement to deliver the required information. Earlier studies explored indoor positioning problems in the context of PVIs using Infrared (Jain, 2014), Bluetooth beacons (Statler et al., 2016; Cheraghi et al., 2017), inertial sensors (Harle, 2013; Kang and Han, 2014) and fusion models (Wu et al., 2007; Guo et al., 2019). Many indoor positioning systems consider uniform accuracy requirement whereas in practice accuracy requirement varies. Indoor spaces very often may not require high and uniform localization accuracy across the whole navigable space. In addition, handling transitions across buildings, and floors inside a building is challenging using smartphone sensors (Muralidharan et al., 2014). Based on aforesaid methods, many solutions are being developed and tested to enable PVIs to navigate independently in unfamiliar indoor spaces like shopping malls (Giudice et al., 2019), hospitals (Rousek and Hallbeck, 2011), railways (Kim et al., 2016), museums (Asakawa et al., 2018), and airports (Guerreiro et al., 2019). Besides this, many specific applications i.e. BeMyEys, Nearby explorer, Lazarillo, Clue, Blind Square are already being used by PVI to get navigation assistance, and route guidance (Swobodzinski and Parker, 2019). There have also been a number of examples of digital systems to aid people in navigating some specific indoor environments My Way is a mobile app to access Boston children's hospital maps and images through GPS over smartphones. Wright used a touch screen monitor to enable users to find 16 pre-selected destinations based on the frequency of use and reported 86 % success in finding the selected destination (Wright et al., 2010). Guerreiro, presented an interactive virtual navigation app in which PVIs can learn unfamiliar routes before physically visiting (Guerreiro et al., 2017). Jaime presented an audio-based virtual environment simulator for orientation and mobility training (Sánchez et al., 2010). Sato presented an enhancement to their indoor navigation work as NavCog3 - a specially designed application for PVIs (Sato et al., 2019). B.S. Tjan presented a digital sign system based on retro-reflective tags printed with specially designed patterns and identified them by a handheld camera and computer vision (Tjan et al., 2005). However, nearly all exist in high resource settings.

Despite having the largest PVI population, very little indoor navigation research and intervention have been demonstrated in low-resource countries (Upadhyay and Balakrishnan, 2021a). In low-resource settings, there is a specific challenge like understanding the context and the diversity of the population. Except for a few working drafts (Director-General for Policy Planning. 2017; Greenroyd et al., 2018), globally there is not much prior work available that can clearly identify the challenges and comprehend what are all accessibility information is required to support indoor wayfinding and accessibility, except a few open information standards came into existence (Giannoumis et al., 2018) until recently. Global coverage of indoor maps is poor, how the digital map will be easily generated with the detailed information at scale is remain challenging and what interface modality can be suitable for a diverse population with visual impairment. This work touches upon the aforementioned question in the context of low resources. To the best of our knowledge, there is no systematic development research exists for indoor navigation and accessibility for PVIs, especially in low-resource settings.

Need Assessment

Some valuable need assessment study for PVIs has been presented in the recent past but is limited to indoor wayfinding in a more structured setting (Ponchillia et al., 2020) whereas assessment of indoor wayfinding and accessibility highly depends on users, environment, regional context, and wayfinding objective (Devlin, 2014). To improve indoor accessibility, another critical aspect is the nature of the information that is provided to a BVI user(Gallagher et al., 2014).

Table 1. The List of Focus Group Participants

(B: Blind; LV: Low Vision; E: Expert; P: Professional; K: Knowledgeable)

Participants	**P1**	**P2**	**P3**	**P4**	**P5**	**P6**	**P7**	**P8**	**P9**
Age	50	42	34	36	38	45	28	58	40
Disability	B	LV	B	LV	B	B	LV	B	B
Experience	P	E	P	E	E	P	K	E	P

Clearly, there is a gap for user-centered design attitude concerning the actual problem – one which incorporates universal and inclusive design principles recognizes the uniqueness of the PVIs and understands the challenges associated with the environment of use. To understand this, we conducted a survey followed by a semi-structured interview with professionals with visual impairment to realize their experiences and challenges.

The objective of the focus group study of PVIs was to gain an insight into their indoor accessibility experience, behaviors, and practices followed by them. This was not restricted to a health care facility alone. This study was carried out with a total of 9 PVIs - 3 low vision and 6 legally blind, ages ranging from 28 to 58 (mean=42, std.=10, 7 Male, 1 Female - P3 in Table 1) including coming from very diverse professional backgrounds. Based on our focus group inclusion criterion, it was difficult to get an expert female PVI with focused expertise. Informed consent was taken from each participant along with their permission to record the conversation. The survey includes a set of past navigation experiences and challenges, limitations, and expected solutions.

Survey Outcome

Based on the initial survey, we found that *hospitals* are the most difficult places for independent wayfinding and *getting the right information, knowing the position, and heading direction* were the major challenges for PVIs during their journey. The *airport* appears to be the least challenging for participants due to limited experience since almost all airlines assist PVIs once they reach the airport. We also found workplaces and metros were most frequently vesting places by the participants. Locate myself and wayfinding could be the most useful application feature as suggested by the participants.

Semi-structured Interviews and Outcome

After the survey, a semi-structured interview was conducted on a similar topic and the session was audio recorded. The average time taken for this study was around 100 minutes for each participant - 30 minutes for the survey, and 60 minutes for an interview with a 10-minute break. All interviews were transcribed, identifying details were omitted and actual names were changed to ensure anonymity. The data was analyzed thematically using an inductive approach to draw themes for wayfinding from an experiential orientation, based only on practical experiences (Thomas, 2003). From the interview data, we were able to code key needs and challenges.

Familiarity of the Built Environment: Information requirement during the indoor journey depends on one's familiarity with the building as well as the critical and transient nature of the "learned" information about the building. While discussing this, P2 suggested, "I have three categories of buildings, one is familiar buildings where I visit two-three times in a month or more, second could be a somewhat familiar building where I know the building but do not visit frequently, maybe once in two to three months and the last could be an unfamiliar building where I visit once in six months or more." Most of the participants suggested a similar three-level classification.

Cues and Landmarks for Building Orientation: In the discussion we found, that to gain the natural orientation inside a building there should be a tactile or a sound landmark that PVIs can identify and learn over a period of time. P1 shared, “The whole orientation is based on landmarks, we always rely on tactile, sound, or smell because they are more reliable landmarks for orientation. To locate a door of a room, foot-mat outside it would help because one can guess where the door can be.” P3 added one interesting experience, if I am guiding a visually impaired person, one interesting landmark is the level change or a speed breaker that I generally mention.” In outdoor settings, people refer to “travel straight and as soon as the speed breaker comes you take a left or count three-speed breakers and then turn right as these are very useful tactile landmarks.” P5 added, “In the case of indoors, sound landmarks like an escalator or a lift opening and closing or humming of a fan at a certain location are useful. Further, if there is any fountain or water flowing landmark that is also useful.” Route knowledge and orientation happen with the help of these landmarks over time but clearly, it also depends on the visit frequency. Some of these cognitive landmarks can be captured over the map and delivered to PVIs for reassurance and orientation.

Prerequisites and Route Preview: Overall journey experience depends on the ease of access to the service offered with timeliness. Prerequisites are the prior information or arrangement required to fulfill the navigation objective. Participants experienced critical miss of doctor’s appointments because of the inaccessibility of printed timings on the appointment card. Another painful experience shared was missing the boarding the train due to the lack of information about platform numbers. Route preview is also a prerequisite and important for navigation planning even among sighted users. It was interesting to understand that route preview can be useful for simple and smaller routes but complex routes require real-time navigation. Route preview can have different levels, ranging from beginner to expert, where landmarks along routes can be appropriately made available to be useful for orientation without the cognitive overload. Many times, it is difficult to get help from other people easily and it's also not safe in this pandemic situation. Here, the route preview can be useful to gain enough route knowledge to feel more confident during way-finding.

Accessibility of Mobile Navigation System: P1 shared "While walking with a cane in one hand whether it's indoors or outdoors, simultaneously holding a smartphone is challenging." Often to use a smartphone, one may need to touch the phone using both hands and, in this process, the cane may lift from the ground which leads to disorientation. P4 shared "my all focus sticks to navigation, I can't afford to do anything else, often in stairs if one hand is holding the cane, the other hand is used to hold the railings or some other support." Though single-hand use of smartphones with talk-back is possible its reliability in general and noisy environments, in particular, is an issue. The implication is that preferably the smartphone-based navigation supports the hands-free operation.

Open Spaces: One participant shared his travel experience, "airports have different challenges altogether because airports have so much open space (he was referring to large halls) there is no corridor anywhere and such open spaces are always a challenge for me". Similar challenges can be seen in campus-like spaces which may have multiple buildings and may require traveling across large open spaces - covered as well as uncovered. Tactile paths are effective in such open spaces to get a path to move but are constrained in the information sense as it is not clear where it is leading to? In places where you can't trail with something like a wall or a corridor, a PVI can quickly lose direction. One possible way could be to break the open spaces using tactile markings and create landmarks that are annotated on the map to support navigation as well as orientation.

A semi-structured interview with participants suggests that the preference for using a wayfinding application depends on its ease of access and utility to the overall navigation objective. For example, P9 mentioned, "I use Lazarillo and it offers seamless integration of outdoor maps and transport applications. I usually book my Uber from Lazarillo itself." The amount of information provided in turn-by-turn navigation should vary based on users' familiarity with the building. Points of interest and information priority along a route encountered in a hospital can be completely different from a shopping mall or a museum. Participants' journey experience indicates that an outdoor-indoor transition remains unaddressed. All of the participants mentioned that finding the right orientation and accessing information along the route are challenging even in popular applications like Google Maps. A route guiding suggestion like "head southwest, and walk around 10 meters" has little significance for PVIs. In a multi-lingual country like India, applications not supporting regional languages are an additional serious issue. Detailed analysis of these studies helped us to generate a set of specifications and help the development of solutions that can substantially improve the indoor journey experience of PVIs. We identified, that functionally a successful indoor wayfinding and accessibility system should provide two essential information with bounded tolerance: the first is the current location and heading direction, and the second is the route to the destination incorporating intermediate points of interest (PoI), decision points. To follow a navigation route, PVIs need to have real-time access to information about the distance and direction to PoI and upcoming turns until the destination is reached. Apart from wayfinding to enhance usability, people also need access to the services associated with a navigable landmark. Such a comprehensive framework to deliver semantic information can also have a universal acceptance since this is useful to mainstream users. These form the basis of requirement specification as well as implemented case studies in the rest of this paper.

Derived Specification

While performing navigation, PVIs pay considerable attention to their other senses to understand their environment better and to identify landmarks and clues hence any solutions should not interfere with these senses. A suitable interface is critical for inbuilt accessibility; the solution would be effective only when it can be easily configured to the level of information required by the specific user in a building. Journey well-being is measured by the overall experience that is close to a sighted assistance throughout the journey (Cupples et al., 2012). Based on these discussions, a set of specifications have been evolved. We categorized them into wayfinding, accessibility, and functional requirements.

Wayfinding Requirement

- Turn by turn navigation is the most acceptable approach in indoor navigation, where access to location and heading direction should be readily available to PVIs.
- To locate an exact door or a counter, a user-triggered Bluetooth audio beacon placed at the door or a counter can be the most interactive and effective mechanism for PVIs [40].
- Route guidance must offer a safer route rather than the shortest or fastest route, both to lower the potential danger of collision as well as loss of orientation. e.g. in corridors, a lane free from protrusions, and door and window openings are safer for PVIs.
- Use both clock and direction references for orientation e.g. compared to the “move slightly at 3 o’clock”, “turn back and then turn slight left” is preferred by many PVIs.
- Predicting the expected journey time is useful information in navigation planning.

Accessibility Requirement

- It should provide crisp and clear audio without being verbose and always respond to queries in all possible states.
- It should allow PVIs to configure their level of vision, choice of language, and choice of interface - visual or auditory and haptic.
- In certain alerts, vibrations can supplement audio e.g. case of protrusions or an impending level change. Similarly augmenting approaching turns with beeps and a confirmation once the turn is taken can be useful.
- To provide alerts at certain situations or changes e.g. for certain PVIs bright sunlight may be a greater problem than dark corridors.
- For mobile apps, the control interface must be optimized for hands-free operation through speech, or control gestures must be optimized for one-hand operation. This has a practical advantage for PVI who also uses a cane for navigation support.

Functional Requirement

- As an integral part of route preview, it should know, and predict (including waiting time) to make the journey planning more effective. e.g. in a hospital consultation, it should include, “Please carry your patient ID number and consultation may take 45 minutes.”
- Whenever possible, it should ensure that PVIs know who is going to attend to them in their journey and what their roles are. For example, in a hospital journey, they may be Junior residents, doctors, or nurses with their roles. The solution must explain the expected journey/waiting time in different stages in real-time.

- It should offer the help for associated services, for example, to be guided to another lab for (eye) dilation, or to book a follow-up appointment after the consultation is over.
- Offer to read any written materials and recognize objects at the facility via AI techniques using a mobile camera.

Implementation Methodology

The framework proposed in this paper is for making an existing indoor space digitally accessible to all, with a particular focus on PVIs based on the above-mentioned specification. To achieve this, we have built two software modules (refer to Figure 1); module one is a custom map annotation tool to capture points of interest and cues from the indoor environment and create digital maps with additional semantic information (including symbolic, functional and operational information). This information is then provided to users of the indoor space through another custom-built inclusive wayfinding application. Wayfinding application is integrated with the indoor space using Bluetooth low energy beacons for localizing users inside a building. The beacons are placed strategically so that the user application can pick up the signals from the beacons and update the current location of the user to an accuracy of 2 to 3 meters (Upadhyay and Balakrishnan, 2021b). Wayfinding applications use smartphones' electronic compass sensors to help the users orient themselves in the right heading direction. Using accurate location, orientation, and step count this application provides turn-by-turn navigation guidance to PVIs.

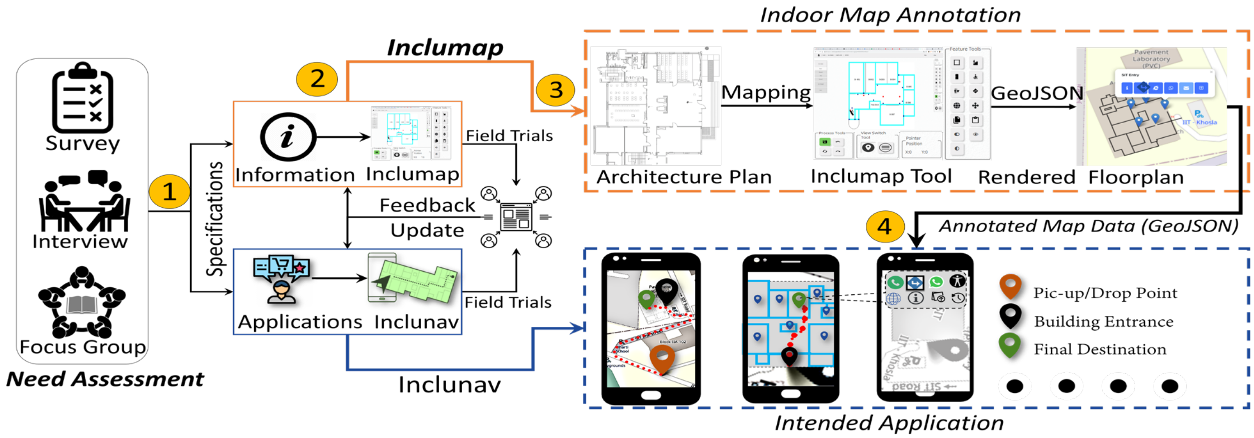

Fig.1. End-to-End Implementation of the Indoor Accessibility System.

Map Annotation Tool

Creating an accurate digital map for indoors with inbuilt accessibility is challenging due to the diversity in spaces and their users (Froehlich et al., 2019). In our survey, we found that organizations managing the spaces typically have architectural floor plans for reference. Besides the building geometry, these floor plans do not contain accurate information and sufficient cues and are often obsolete as it doesn't reflect changes to the building structures that have occurred over time. These floorplans are often in non-editable format (IFC, DWG or PDFs), and thus the organizations cannot incorporate the changes. Considering the need for an accessible digital map with rich information cues, the annotation tool has been developed over a web app2, which starts with an existing floor plan in a standard file format (i.e. '.pdf', '.jpg' or '.png'). The building information is categorized by venue (a campus or set of buildings within the same area), and further divided into individual buildings, and their floors. The annotation tool can be used to mark the identified non-walkable areas, key landmarks (including functional and operational info.), accessibility services, and connections between floors (staircases, elevators), buildings (pickup, drop-off points) and local-global reference points. The annotating process has been divided into two stages, pre-processing and map annotation using the IncluMap application.

Annotation Tool Design Strategy

The proposed annotation tool is a progressive web application. Tools front end has been designed in Html-CSS-JS whereas the back-end is in NodeJS. The annotated map data is stored in a graph database (neo4j) and can be accessed by the wayfinding application using cypher queries from building data APIs. Functional requirement of navigation application such as localization, path planning, and route captioning is also supported by annotated map data. Other supporting requirements such as map data security, privacy, and access have been implemented separately. Building/facility authority can provide public access (all users) or controlled access (registered users) to their annotated maps. Flow in terms of landmarks for all the user functions supported by the facility can be added as a layer on top of the map data and can be changed when required without any changes to the underlying map structure.

Data Type: All the annotated map data is stored in a map data server in a graph DB(neo4j) in GeoJson format. Annotated map data is useful for integrating into other custom applications beyond navigation. Multi Floor Annotation: The annotation framework can handle the interconnection between floors. In a building, floors are connected using floor connector points i.e. stairs, lifts and ramps. There is a direct connection between the same-named connector points. For example, a “Lift-1” on level 0 is connected to all the “Lift-1” on all the other levels. Using the building’s pickup and drop point and floor’s connector points, a graph is generated whenever the user searches a path in the wayfinding application. Figure 2 shows an example of how a graph is created when a user searches a path from a location on the Ground floor(“a”) to a destination location on the Third floor (“b”) of building one.

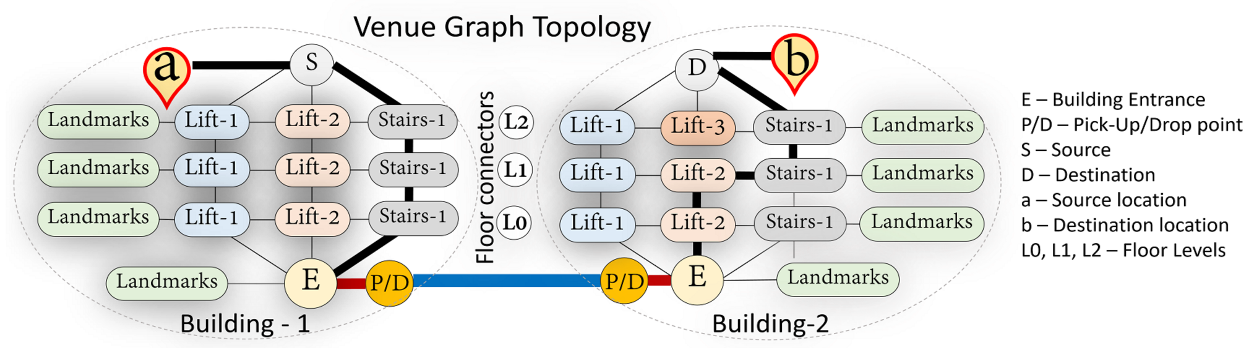

Fig.2. Venue Map Graph where Floors are Connected Through Stairs and Lifts and Buildings are Connected Through Pickup and Drop-Off Points (P/D).

Black lines indicate edges between the nodes whose weights are also calculated while building this graph. In this case, building one is having a connector point (“Stairs-1”) across all floors. When there are multiple connector points in the source floor, the user is shown multiple path options and their distance, each passing through different connector points in the source floor. The user can choose any one path among them for navigation. User-based customization can be used to reduce these options - some may be non-applicable (e.g. stairs option for wheelchair users).

Pickup and Drop-off Points (PDPs): Wayfinding accessibility requires seamless integration of outdoor-indoor transition. This can also be helpful for a campus where mobility among buildings may be required. An annotation tool provides an option to mark the PDPs of a building along with a route to the actual entry door as shown in Figure 3(c) to assist with the outdoor-indoor transition. Within the wayfinding application, PDPs localization has been performed through GPS and the actual entrance of the building is identified by installed Bluetooth beacons at the entry door.

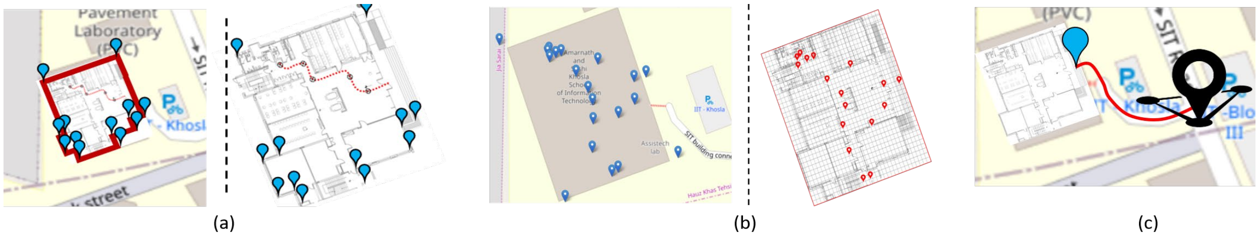

Fig3. (a) Reference Points Selection. (b) A Local Grid to Global Map Conversion. (c) Annotated Pickup/Drop Point and Route to the Building Entrance.

<u>*Local Grid to Global Map:*</u> In the proposed annotation tool, map annotation is performed in a local grid map at the resolution of 30 cm X 30cm. To make the annotated grid map compatible with the world map, conversion from the local grid map to global latitude-longitude is performed using local-global reference points of the building. These reference points are captured during annotation as shown in Figure 3(a) and conversion of local to global point of interest is shown in Figure 4.

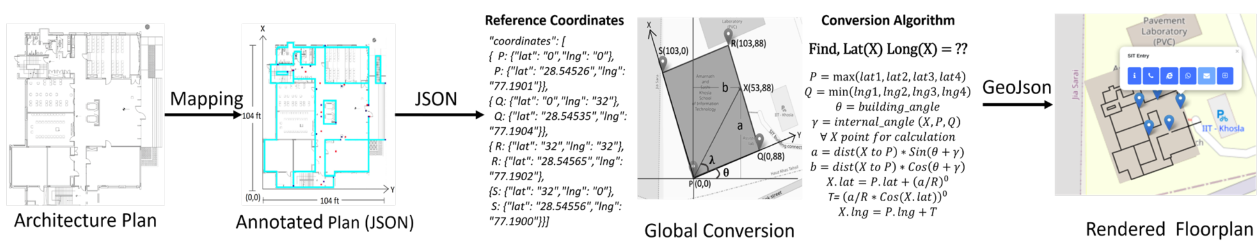

Fig.4. Local to Global Conversion Takes Buildings Data and References Coordinates as Input.

This also helps in generating a global to local conversion of PDPs and outdoor points of interest to support navigation during outdoor to indoor transition.

Wayfinding Application

Once the digital map has been created, the next steps involve the strategic installation of Bluetooth beacons and integration with the digital maps. The purpose of the wayfinding application is to create a suitable user interface to localize the users inside the building to deliver location-based information relevant to navigation and accessibility.

<u>*Location of Beacons and Other Tags*</u>*:* Small floor plans can be analyzed manually to identify the points requiring high localization accuracy (points for installing the beacons) but this may not be feasible for larger floor plans. Once the digital maps have been created, the annotation tool uses the beacon profile, operating environment, and accuracy requirement to suggest the locations for beacon placement. The placed beacon location can be marked on the floor plan with their MAC addresses, using the annotation tool. The annotated building and beacon data are provided to wayfinding applications through a building data API. Apart from the beacons, we also deployed April tags (Similar to QR codes), to easily recognize the doors through mobile cameras. The April tags can be accessed by scanning and are typically useful for low vision and sighted users and augment certain visual/audio information for a particular location or a service. We found additional braille sticker/tactile markers on the TAG with a “standardized” installation protocol that can make them accessible for persons with blindness.

<u>*Localization:*</u> All navigation systems require initialization as well as access to relevant data - the venue, building and the floor of interest to the user. It is important to initialize the mobile device with some accurate estimate when the user is stationary, we refereeing this as instantaneous localization. Once the initial location is known, the destination searches for the shortest feasible route based on the given map data and provides an initial location and heading direction on the map. After the user takes the first few steps, the motion (using a smartphone inertial sensor) measurement predicts, and range measurement corrects the location estimate using the Bayesian model until the motion estimation is reliable. Infield implementation, after getting a valid beacon list (common list from scanned and building beacon list), system-level localization is performed through a context-aware fusion. This has been implemented through a fusion of histograms and an extended Kalman filter (Sakai et al., 2018; Chanana, 2020). Considering the localization

accuracy requirement inside a venue, the proposed system uses a histogram filter for instantaneous position estimate (using only beacons and map) and an extended Kalman filter (EKF) for an in-route position (using both motion and beacons). Instantaneous localization provides an accurate pose estimate in case of stationary position or unreliable motion measurement (i.e. in case of turn/junction/decision points) whereas in-route localization using EKF provides better pose estimation during movement.

Orientation: Orientation is critical to identifying heading direction. The initial orientation is calculated with respect to the true north in the local grid from the current location to the next intended turn. While navigating, orientation loss may occur due to veering from the original path due to crowds or errors in sensor measurement. Empirically we found that turns/junctions are more prone to orientation errors. Our proposed mechanism checks the location and performs the reorientation step at every turn/junction to ensure the correct orientation.

Path Planning: Most path planning algorithms use some variant of the shortest pathfinding algorithm i.e. Dijkstra or A-star to support indoor navigation for PVIs (Wu et al., 2007). Shortest path planning adds unnecessary smaller turn/curves due to shortest path selection. This increases navigation complexity and more prone to collision due to veering, and errors in location estimation. In comparison to rectilinear, slight turn(left/right)/curve adds to path complexity but does not add many benefits in reducing the path length. To fit the navigational needs of PVIs, we implemented a path refinement strategy where turn with small path length was converted to their rectilinear equivalent. Studies have shown, that PVIs had a tendency to linearize curved paths (Ungar, 2018), hence rectilinear path refinement provides a better correlation in comparison to curved paths and reduces the risk of collision at turns in narrow corridors as shown in Figure 5. In the case of PVIs navigation, stride length varies with the height of the users, and crowd density in the navigation space. Our application supports users to specify their height in the profile setting.

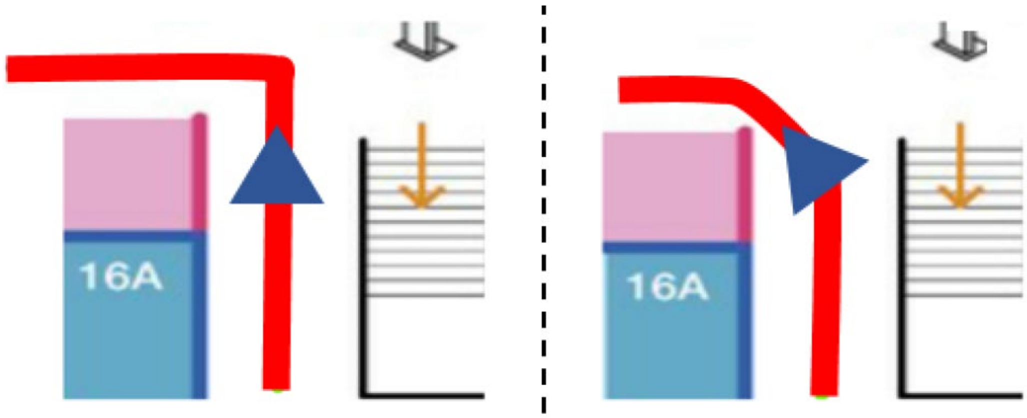

Fig.5. Path Improvement (Left) Due to Rectilinear Path Planning.

Route Captioning and Information Delivery: Route captioning returns the sequence of instructions along the selected route (refer to Figure 6). The level of details along a route depends on the familiarity of the route, the nature of landmarks, and its accessibility. The major information category includes positioning information, orientation information, navigation information, landmark information (this includes in-route landmark and point of interest), and accessibility information (includes obstacle, micro-orientation, surface/light intensity changes, functional information i.e. timings, contact, etc.). To fit the real-time navigation need it was important to keep the instructions short and crisp to avoid information overload and synchronization lag. We found blind users prefer path length in steps whereas low vision prefers meters. All the route and landmark information were provided in audio whereas the combination of beep and vibration was the more effective medium for turns and alert.

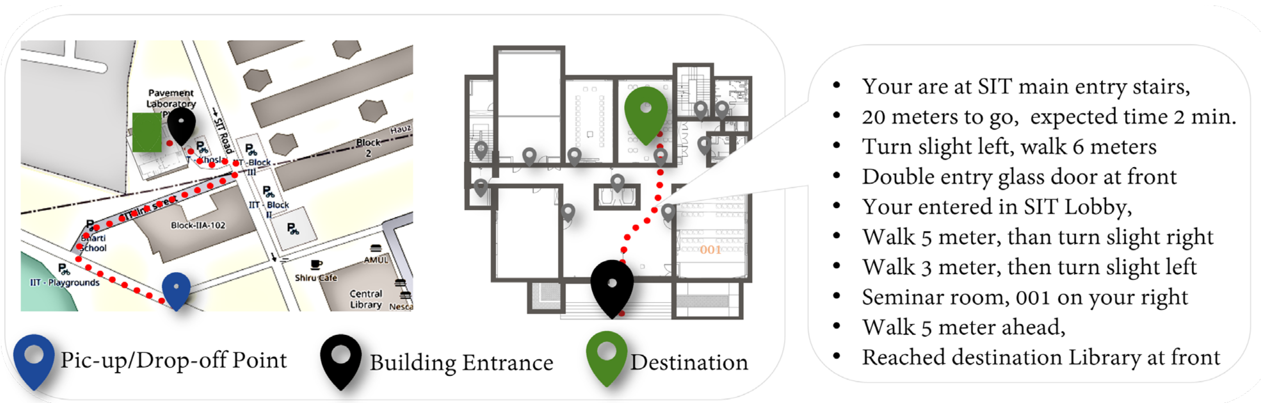

Fig.6. Turn by Turn Route Instruction for a Selected Route.

Integration of Map Data with Localization Infrastructure: Once the indoor localization infrastructure has been installed and integrated with the digital map, the information is available for users to access through the wayfinding application. This application can identify the initial location of users and the user can choose a destination and the application will generate the route requiring the least effort to navigate. During the navigation process, the application provides information cues related to upcoming turns, nearby landmarks, points of interest, accessibility cues such as floor-level changes, and other directional information required on the route. Users can choose to receive detailed information for new locations, and brief information for previously visited locations. The application has been designed to suit the requirement of a large spectrum of visual ability persons. High contrast interfaces make legibility easy for people with low vision or color blindness. The application also factors the security and privacy requirements of an organization managing their indoor spaces by using two-factor authentication systems and capturing the minimum data required. To make it acceptable to a large number of users, the wayfinding application interface has been designed to meet the W3C Accessibility Guidelines for user interfaces and provides turn-by-turn navigation through both visual and audio feeds. This version of the application is an upgrade over the previous and includes the inputs received from the focus group along with the feedback from earlier work (Upadhyay and Balakrishnan, 2021a).

System Evaluation and Discussion

Objective and Method

The objective of this study was to evaluate the utility of the proposed framework for the ease of indoor navigation and accessibility for PVIs. A brief orientation about the study and uses of the IncluNav wayfinding application was conducted with participants. After orientation, an application utility experience study was conducted with participants to evaluate the accessibility of application functionality. Informed consent was taken from all the participants along with their permission to record the trials. An evaluation was made based on task success rate, completion time, difficulties encountered in a task along with their qualitative experiences.

Study Environment and Task Configuration

Due to the ongoing COVID situation, all the safety measures were taken during the trials. A total of 5 PVI participants (2 Low vision, 3 Blind, mean age: 30, std. deviation: 8.4) have been selected for this study. Four participants were college students while one was a working professional. This trial was conducted in one of our campus buildings and consisted of two sets of studies - one is functional experience testing and the other is a goal-directed navigation objective using the IncluNav application. Objective 1 included a *journey from the buildings Pickup/drop-off point to the actual entrance* (Total length: 26meters, Number of turns: 4, Point of interest:2, Nature of the route: Outdoor-Indoor). Objective 2 included *a journey from the building entrance to the faculty lounge*, Second Floor (Total length: 28 meters, Number of turns: 6, Point of interest: 4, Floor transition: one, None, Nature of the route: Indoor)

Result and Discussion

Study 1: Functional Accessibility Experience Task: After initial orientation about the study and application, participants were asked to perform the six functional tasks on the application. The six tasks were – (i) Sign up/login, (ii) Find my location, (iii) Select a destination, (iv) Find heading direction/orientation, (v) Find nearby landmark, and (vi) Profile setting. After completion of each task, the time required to complete the task, and task success rate were recorded and a qualitative rating was taken from the participants on perceived difficulty. Due to space constraints, detailed results of this study are not included. In study 1 above, we calculated the averages of task success rate (TSR), perceived difficulty (PD), and overall scores for each task based on participants' performance. Although the number of the participants was few the results show that finding a location, selecting a destination, and profile setting was easy for the participants whereas finding heading direction and nearby landmarks was difficult in their first attempt. Finding a heading direction was difficult due to the rapid angular motion of participants and the lack of continuous feedback from the application. We observed participants learned this quickly when they repeated the exercise. Sign-up was a little prolonged due to OTP verification, password selection, and profile details (height, vision and route information choice). An overall score (Task success score + difficulty score) for individual tasks except finding heading direction and sign up was above 7 (avg. score = 7.85) in the first attempt, which can further improve with usage. The sign-up and heading direction were found to be difficult (avg. score = 5.9) and would need some redesign.

Study 2: Goal-Directed Navigation Tasks: Participants were asked to complete the goal-directed navigation tasks using the application. Total travel distance, error due to veering, and time is taken to complete the journey were recorded and are presented below.

Outdoor Indoor Transition Task: The first navigation task was to reach the building entrance from one of the PDPs. In our field trial, we found that mobile GPS was able to successfully log the PDP location with around 5.2 meters of error in the local grid map. Orientation is challenging in all existing apps e.g. google map suggests turning southwest which makes no sense for PVIs. This was calculated using a mobile compass and expected heading direction with an average error of fewer than +/-10 degrees and was provided to participants in local direction reference (i.e. turn slightly left and walk 20 meters.) Tactile landmark (glass doors and stairs) along with beacons was intuitive to identify the actual entry door. Most of the participants were relying on tactile information for reassurance if it exists (stairs at the entry point and push/pull glass entry door in this case). Table 2a shows the outcome of the navigation task from pickup and drop to the actual entrance of the building with travel distance time and error.

Table 2a. Outdoor-Indoor Transition Task.

(OE: Orientation error, PDPL: Pickup-drop point localization, MEL: Main entry localization, S: Success, F: Fail)

Participants	**OE (in +/- degree)**	**PDPL error in meter**	**Drift in meter**	**Distance in meter**	**MEL error in meter**	**Time in second**	**Task Status**
P1	8	3.8	5.5	37	1.8	96	S
P2	14	4.2	7.8	33	2.2	93	S
P3	10	5.4	7.5	31	1.7	95	S
P4	18	6.1	9.4	44	5.6	108	F
P5	10	4.2	5.2	33	1.9	93	S

Outdoor indoor transition is not supported by any of the existing navigation applications. Our effort to support this transition for PVIs was found effective in this preliminary study with 4 out of 5 participants being successful in reaching the actual entrance of the building. Our application was able to correct the orientation with an avg. the error of +/- 12 degree which was sufficient for direction guidance. Drift due to veering is one common problem in navigation tasks but is less encountered indoors. Avg. drift (Sum of drift along the path) was around 7 meters for an actual path length of 26 meters with 3 turns. Our proposed system corrects the drift at every turn. The participants (except P4) were able to reach the actual building entrance with an average localization accuracy of close to 1.9 meters without an additional localization medium. We found the description of the entry door (i.e. Near SIT entry, "stairs having 8 steps", and at SIT Entry, "a push-pull, glass door") was quite helpful for participants to navigate to the actual entrance.

Indoor Navigation Task: After reaching the entrance, participants were localized by the beacons, and a notification was played about route preview ("Faculty lounge, 28 meters away, on the second floor"). The second navigation task was to perform indoor navigation from the main entrance to the faculty lounge (Second floor). A set of observations has been recorded and presented in Table 2b. Indoor navigation observations show that the average drift (sum of drift along the path) was 2.64 meters for a total journey distance of 28 meters with 6 turns. This compares well with outdoors because of constrained walking spaces and frequent turns. Time taken to complete the journey was largely due to the increased number of turns. P3 and P5 were reoriented by the application due to motion in the wrong direction which added additional turns but ensured route correction. Waiting time at the lift was excluded in journey time computation.

Table 2b. Indoor Navigation Task. (S: Success)

Participants	**Total Turns (minimum turn: 6)**	**Drift in meter**	**Distance in meter**	**Time in second**	**Task Status**
P1	6	2.1	31	122	S
P2	6	2.5	30	128	S
P3	8	2.9	31	132	S
P4	6	2.6	30	125	S
P5	9	3.1	32	141	S

Semi-structured discussion with participants was analyzed to understand the effectiveness of the proposed framework to support indoor navigation and accessibility. We found the tactile landmarks (push-pull glass door, doormat, fingerprint access near door) are more prominent and easier to recall for PVIs just like visual cues for sighted hence contributing to the cognitive map. Sound (i.e. lift or a fan) and smell (cafeteria or a lab) are cognitive landmarks but not abundant indoors. This outcome reinforces the fact we discussed the earlier representation of information in such a way that can make a space more interactive and accessible for PVIs. In the task execution, we tried to analyze the utility of route preview and found it to be highly biased with memory and was not a preferable choice for PVIs especially for the blind if real-time navigation is available. However, low vision participants were able to follow the route preview to reach their destination for simpler routes having < 4 turns. One interesting finding was to create a mental map and route knowledge A detailed and perceivable feature description is important. The discussion reveals that the feature correlation was easy for the participants with significant independent navigation experience, due to better special motor skills. These trials were conducted in a controlled environment due to COVID restrictions. From our trial, we found that crowded, noisy, and open spaces were more prone to error for PVIs. In the wayfinding app, a course correction was made with bearing measurement at every incoming turn, and orientation was found to be accurate even on a long trail. To support error recovery if a user went in the wrong direction, applications re-route the users from the current location to their destination. Route information from building prior have been used to estimate the grid likelihood to recover smaller errors during navigation task.

Conclusion

In the context of a low resource setting, we have demonstrated how the proposed tools based on an inclusive framework can be used to create a system-level deployment to support indoor wayfinding and accessibility. The proposed solution can be scaled and evolve as a standard framework for providing not only navigation assistance but also provide access to relevant information and services to large-scale indoor facilities. This can lead to a universal acceptance of the proposed solution since increasing indoor functionality and services add to the information load hence its accessibility. The annotation tool developed in the project has been designed to accommodate a variety of information cues relevant for accessibility, wayfinding, and functional access keeping PVI as prime users in a context low resource setting. Users of the annotation tool may also come from a variety of backgrounds, with varied digital literacy and spatial understanding of indoor spaces, thus appropriate interfaces and automation features can simplify the process. Although the proposed mapping application has multiple manual involvements to create accessible digital maps and has a scope for improvement, we believe this can be a useful contribution to creating more indoor maps and accessibility data at scale. At this moment we are engaged with organizations owing public spaces like universities and hospitals to create a standard operating procedure for setting up a digital map of buildings to communicate, wayfinding, accessibility, and functional information to their user over an accessible medium i.e. smartphones.

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