9-2014

NavPal: Technology Solutions for Enhancing Urban Navigation for Blind Travelers

M. Bernardine Dias
Carnegie Mellon University

Follow this and additional works at: http://repository.cmu.edu/robotics

Part of the Robotics Commons
Abstract

In this report, we describe our vision for computing technology tools that can enhance the safety and independence of blind and visually impaired people navigating unfamiliar indoor environments. We describe the overall roadmap for our work, along with the research to date on each component of this roadmap. This set of tools, known as “NavPal”, combines a variety of techniques and technologies including robots, crowdsourcing, advanced path-planning and multi-modal interfaces. All of these tools and the framework have been informed, tested, and endorsed by many blind and visually impaired adults, and by several Orientation and Mobility experts.

1. Introduction

Assistive technology plays a key role in the independence and safety of people with disabilities. For blind and visually impaired (B/VI) people, appropriately designed and well implemented assistive technology can additionally make a significant difference in education, social acceptance, and productivity. We have been working with B/VI communities around the world on a variety of assistive technology projects for almost a decade, with a more recent focus on technology tools for wayfinding and navigation. Given the availability of some tools to assist B/VI travelers with navigation in outdoor environments, our focus has primarily been on indoor environments and scenarios that necessitate transitions between outdoor and indoor environments. Because visual impairments can vary widely, the corresponding needs and preferences for tools and interfaces can also vary accordingly. Our work addresses this wide range of needs and preferences by exploring a suite of relevant tools that can accommodate several options for customization by users. Our approach also recognizes the current limitations of technology and the capabilities of the B/VI travelers by designing assistive mechanisms that value input from humans, and therefore are
essentially human-machine solutions. Another key element of our approach is a strong focus on needs assessment and iterative design with relevant user communities as shown in Figure 1. Therefore, the problems we address in assistive navigation, and the tools we design are heavily influenced by feedback from a variety of users in the B/VI community and relevant Orientation and Mobility (O&M) experts.

Findings from our needs assessment revealed several concerns of B/VI travelers. First, they pre-plan their navigation routes as much as possible and need to build a mental map of the new environment they will be navigating. Once in a given indoor space, they need to orient themselves in that location so they can identify where they are at any given time. Next, they need to figure out how to navigate to and from the location(s) of interest from a known environment. They also need to be informed of dynamic changes to the unfamiliar environment which may impact their safe navigation. Furthermore, they need to be able to “record” their navigation experience for future trips and also potentially share this information with others who might find it useful. Finally, if they get into any unsafe or difficult situation while navigating the unfamiliar environment, they need to have a reliable means of getting help. These findings support conclusions from previous
work in this area and also align with the methodology adopted by O&M experts.

In order to orient themselves in an indoor environment and help identify their location, B/VI people rely heavily on landmarks and clues around them. Landmarks and clues can include elements such as doorways, changes in elevation, or distinct sounds and smells. During navigation, B/VI travelers depend on a mental or cognitive map of the space that they may have previously constructed and also use methods such as counting the number of landmarks or clues in their environment. If lost or disoriented, they typically ask for assistance from sighted people in the vicinity, although instructions from many sighted people are usually not specific enough to be useful. They also sometimes seek assistance from owners or managers of a specific facility they are visiting, O&M specialists (if it is a location they need to navigate frequently), or other B/VI people who are familiar with that location.

Effective indoor navigation and wayfinding tools should not only assist B/VI users to navigate indoors, but also seamlessly integrate with outdoor navigation guidance, transit assistance, and other assistive services that enable B/VI travelers to safely and independently traverse urban environments. This means that urban navigation aids for this population must incorporate accessible interfaces that allow B/VI users to both receive and convey information, and must be customizable to accommodate individual preferences. These tools must also be capable of indoor and outdoor localization at the resolution necessary for B/VI travelers. Access to maps and other information in a variety of forms will also be critical so that routes that adhere to sensory and other constraints can accordingly be planned. Finally, to truly empower B/VI travelers, assistive tools should provide mechanisms for advocacy to improve accessibility within the larger framework of the city infrastructure. This is because any attempt at making indoor spaces more accessible to B/VI people has to be a concerted effort of innovators, law-makers and users. For example, new
accessibility standards may need to be introduced to improve the safety and independence of B/VI people navigating indoor environments. Promising technology solutions for wayfinding and navigation in these environments could help inform these accessibility standards in the future.

Our research in assistive technology over the past few years has been exploring how computing technology tools can enhance the safety and independence of visually impaired people navigating urban environments, with a focus on unfamiliar indoor spaces. Our work began with a smartphone application designed to provide dynamic localization and path planning assistance to visually impaired people as they navigate indoor environments. This work soon evolved to address the more complete needs of the B/VI community in the area of indoor navigation. In this report, we describe the overall roadmap for our research in this area, along with the specific tools we have designed to date in each segment of this roadmap. This suite of tools, known as “NavPal”, combines intelligent robotic systems, Wi-Fi-based signal strength estimation, constrained path-planning and multi-modal interfaces towards improving the overall safety and reliability of navigation for a variety of B/VI users.

Figure 2 Necessary components of urban wayfinding and navigation for blind and visually impaired people
The envisioned roadmap to the NavPal suite of tools is illustrated above in Figure 2. Each segment of the roadmap requires a set of assistive technology tools to enhance urban wayfinding and navigation for the B/VI community.

The goal of the NavPal suite of tools is to provide B/VI adults with customized guidance options during each phase of their travel in urban environments; beginning with trip planning, continuing through safe arrival at their destination, and ending with recording and sharing relevant information learned from each trip. Envisioned examples of NavPal components are a floor-plan editing tool that allows building managers to easily create and edit floor-plans in a format that can be easily made accessible to visually impaired people, enhanced route-planning algorithms that efficiently plan safe routes for B/VI users, and customizable user interfaces that effectively communicate route information with sufficient resolution to a variety of B/VI users. The NavPal suite of tools and the corresponding roadmap have been informed and iteratively designed with the input of many B/VI adults and several O&M experts. This work is strongly endorsed by all of these participants. The rest of this report describes the NavPal roadmap and its components in greater detail with a focus on indoor wayfinding and navigation.

2. Trip Planning and Accessible Maps

Most B/VI people always plan trips in advance as much as possible. In fact, many blind people will not travel to unfamiliar locations unless it is possible to pre-plan most of the trip. Existing trip-planning tools do not take into account the variety of challenges and the complex components of trip planning that begins with leaving the home, do not allow customization for constraints and preferences of B/VI travelers, and are not able to accommodate a variety of the transportation modes commonly used by B/VI people. Therefore, an important tool envisioned for NavPal is an assistive trip planner that addresses these shortcomings. The NavPal trip planner will be one of the
last components of NavPal to be designed and implemented since it must integrate information from most of the other NavPal components. Therefore, we have not yet focused much effort on this tool to date. A highly relevant component of trip planning is having access to useful maps. For the B/VI population, this translates to accessible maps, that is, maps in formats that are accessible and have sufficient and relevant details for B/VI travelers.

A major obstacle to B/VI people pre-planning trips is the lack of accessible maps for indoor environments. A survey of property managers revealed that the primary reason for this roadblock is the lack of tools to create and maintain accessible maps of the facilities they manage. Furthermore, there is no single authority or commercial solution that maps indoor areas like the widely available outdoor map equivalents. Therefore, a solution to accessible indoor maps is likely going to take a different form than its outdoor counterparts.

Towards further understanding the challenge of accessible map creation, we interviewed five building managers from a mix of for-profit and nonprofit organizations about the variety of difficulties that can arise in making their locations accessible to B/VI visitors. Most buildings have one or two main entrances, so they employ a front desk attendant to provide directions to visitors and to prevent unauthorized visitors from entering the location. These front desk attendants are often instructed to warn B/VI visitors about obstacles that they might have difficulty avoiding unless the visitor is escorted by someone who can guide them through the building. While many buildings have room numbers displayed in braille, they do not have braille directional signs to help guide B/VI visitors. An additional complication is that many B/VI people do not read braille. Special events that alter the regular configuration of an environment, constructions or maintenance, and architectural features such as spiral stairways can cause additional navigation difficulties for B/VI visitors. Additionally, floor-plans are not always maintained accurately as
buildings undergo alterations.

In general, B/VI visitors are expected to be able to navigate buildings by themselves or bring their own guidance assistants with them when they visit most indoor environments. Most building managers and front desk attendants also have limited knowledge about the challenges of B/VI people and are not always able to assist in useful ways. All of the building managers we interviewed agreed that a tool for creating and maintaining accessible maps would be very helpful. Important features in an accessible map creation tool identified from these interviews are briefly described below:

- **Feature classification**: The ability to classify rooms, halls, doors, and types of doors
- **Annotation of connectors**: The ability to annotate doors, elevators, regular exits, and emergency exits
- **Naming areas**: The ability to label spaces at different granularities (e.g., office numbers, building names)
- **Map updates**: The ability to easily update maps when the environment changes or an error is discovered
- **Using existing blueprints**: The ability to import images/blueprints of floor plans in a variety of file formats and edit them as needed
- **Automated information extraction**: Automated information extraction from imported blueprints where possible and the ability to easily edit the resulting maps
- **Privacy control**: The ability to designate areas of maps as private and make other areas of maps publicly accessible or accessible to specific people
- **Effective interface**: An intuitive interface that is easy to use
- **Automated accessibility feature insertion**: Automated conversion of resulting maps to
We developed an initial prototype for a floor-plan creation and management tool that can better equip building managers to create and maintain accessible maps of their buildings and surroundings. This initial prototype was implemented under our guidance by a group of students in the “software development for social good” course at Carnegie Mellon University. The primary menu for this tool is shown in Figure 3. The tool allows users to upload existing images of floor-plans, which are converted to an editable digital format. Image processing techniques are used to identify and label relevant features. First, line extraction identifies all straight edges in each floor-plan image. These lines that are in close proximity to one another are then merged to reduce errors. The resulting automated identification of walls is then further modifiable by the user. After line identification, the auto-detect process identifies square areas which could indicate where doors are potentially located. Feature detection is then used to isolate and identify potential doors in the floor-plan image. Finally, text recognition is used to extract any labeled areas (such as room numbers and building names). The text is first isolated by identifying conjoined lines and then Tesseract is used to perform OCR on the isolated text.

Figure 3 Initial prototype of floor-plan creation and management tool
This automated process of extracting information from the uploaded floor-plan images, dramatically reduces the amount of work the user has to do to convert existing floor-plan images into accessible maps. Additionally, the prototype tool allows users to draw new walls, complete rooms, label areas, add doors, and perform other typical edit functions. Initial user feedback from building managers on this prototype was very positive, and we are currently creating a more enhanced prototype that incorporates initial user feedback. Our initial methodology for creating accessible maps is to convert them into a format that can be interpreted by the other NavPal tools and thus be used by B/VI people via the accessible interfaces on these tools. However, we are also working with relevant experts to explore ways in which these floor-plans can be made more accessible via screen readers and other currently ubiquitous tools. Next we describe our vision for how accessible maps can be used by B/VI travelers to familiarize themselves with indoor locations and plan effective routes through these spaces.

3. **Familiarization and Route Planning**

Once we have accessible building maps, we need tools that allow B/VI people to familiarize themselves with these environments so that they need fewer interventions from others when they travel to unfamiliar locations. Depending on how frequently a B/VI person needs to visit an unfamiliar location, he/she may get help from a friend, an information line/desk at the location, a sighted person in the vicinity, or an O&M specialist as needed to construct a corresponding mental map and learn how to navigate that environment. While we do not envision humans being completely removed from this process, technology can certainly play a greater role in enhancing the independence of B/VI people in this familiarization. Towards this end, we have begun to explore several options for developing a familiarization tool that can take advantage of the accessible maps generated by the NavPal tool described in the previous section, and that
interconnects with the other components of NavPal including the route planning tool and trip planning tool. The most promising avenue for this familiarization tool is the use of virtual environments.

Our vision for the NavPal familiarization tool is to transform the accessible digital maps into accessible virtual environments that B/VI users can explore to build detailed cognitive maps of each environment before physically interacting with that environment. The virtual environment can be represented using audio cues and sounds associated with objects in the environment. Additionally force-feedback via a joystick and vibrations can be used to guide the B/VI users and alert them to obstacles and objects of interest in the virtual environment. We are currently exploring methodologies for constructing these virtual environments from accessible digital maps, and effectively enabling B/VI users to familiarize themselves with these environments.

Once visually impaired travelers have familiarized themselves with an environment, they often like to plan routes within that environment that will allow them to effectively traverse between key locations such as the entrances and exits to the building, restrooms, elevators, cafeterias, meeting rooms, etc. When planning routes for visually impaired adults, several aspects are notably different from route planning for sighted adults. For example, the routes need to be optimized for different objective functions such as minimizing turns, maximizing traveling through areas where others may be present in case of needing assistance, favoring paths where the traveler can follow a wall closely, and ensuring the chosen routes have as many accessible landmarks and clues as possible. To learn more about these route planning needs and preferences of B/VI people, we created a simple web-tool for B/VI travelers using screen readers to pre-plan routes within a small set of indoor environments.
This NavPal routes web-tool (shown in Figure 4) provides the user with the option of selecting a start and destination from the available sample locations and provides route information for walking between the two locations. The user is first allowed to select a building and then select a location within that building as the start and goal locations. Buildings and locations within each building are provided via drop-down lists. The web-tool is designed to be accessible for B/VI users via screen readers and was tested with some of the most commonly available screen readers. We further tested the accessibility of the tool using WAVE, the web accessibility evaluation tool provided by WebAIM. For the purpose of this initial investigation of needs and preferences, fictitious route information was used. However, several route planning algorithms are available to plan effective routes given specified user constraints and preferences. Before exploring the route generation aspect of this work, we wanted to understand the interface constraints and how useful this tool will be to the target population. A survey of B/VI adults confirmed that this tool will be very useful and provided several insights into the range of needs and preferences that must be taken into consideration when converting this prototype into the final NavPal route planning tool.
We are currently implementing this tool and expect it to be able to use the NavPal accessible maps and provide input to the NavPal dynamic guidance tool described in the next section.

4. **Transit Assistance, Dynamic Guidance, and Seeking Assistance**

The role of computing tools is not limited to trip and route planning. Assisting visually impaired travelers with dynamic guidance during transit and indoor navigation, and with seeking assistance during the trip is the next critical challenge. These tools can help in situations where unforeseen dynamic situations arise (e.g., an elevator being out of operation) and also allow for reminding the traveler about aspects of the route that he/she has forgotten. In addition, if needed, the tools can assist the traveler in seeking assistance from others in the environment or guiding the traveler to safety. It is essential to view these tools as human-machine systems since it is important to ensure that the traveler is able to use his/her orientation and navigation skills in this process.

While transit assistance is usually considered outdoor navigation or assigned to a special category, there are indoor components to transit that are important and hence we include transit assistance in this description of the NavPal suite of tools. This tool is useful for example when navigating large transit stations such as airports and train stations. We are currently investigating the needs and constraints that must be considered when designing a tool that can assist B/VI travelers with navigating the unique aspects of transit stations.

To address dynamic guidance during indoor navigation in more general locations, we developed an Android smartphone tool, shown in Figure 5, that integrates indoor localization [3], sparse map-representation [1], and an accessible user interface [2]. Specifically, we developed a navigation solution that combines dead reckoning (DR) and Wi-Fi signal strength fingerprinting with enhanced route-planning algorithms to account for the constraints of B/VI users to efficiently plan routes and communicate the route information with sufficient resolution. The localization
component of this initial work used a small wheeled robot to initially map the indoor environments and build a database of Wi-Fi fingerprints. This P3DX robot was retrofitted with a laser rangefinder for obstacle detection and mapping, and fiber optic gyroscope for localization. The robot was remotely operated to roam a building carrying a smartphone and thereby constructed a Wi-Fi signal strength map that corresponds to the building map generated by the robot’s sensors. The smartphone app was then able to use this Wi-Fi map to localize the user during navigation. The interface component of this prototype used simple on-screen gestures and a combination of voice and vibration feedback to allow B/VI users to interact with the tool. To evaluate the feasibility of our solution, we developed a prototype application on a commercial smartphone and tested it in a small sample of indoor environments.

Figure 5 Initial prototype of NavPal dynamic guidance tool implemented on a smartphone

The map of an indoor environment was represented in this prototype using a variation of hierarchical maps to accommodate dynamic changes while maintaining a compressed representation suitable for a smartphone [1]. In this representation, indoor locations were represented on a map as nodes on a graph and the map was split into sub-graphs. A variation of the D* algorithm was used to efficiently plan and re-plan routes dynamically despite the limited computing power available on the smartphone [1]. More specifically, in this hierarchical map representation, low-level maps used for
higher-resolution navigation within rooms and hallways represented individual rooms with significant spatial detail without having to represent the spatial relationships to other rooms. Complementarily, high-level maps used to generate plans for coarse navigation between floors and rooms represented larger areas of a building while omitting detailed spatial relationships of individual locations inside rooms and corridors. In this prototype, high-level maps were represented as graphs and low-level maps as grids. The high-level route planner first searches for an optimal path on the graph and provides a restricted set of nodes to the low-level route planner. This grid planner then traverses the provided nodes and generates a higher-resolution path to the destination.

![Figure 6 Examples of wayfinding information that could be presented to B/VI users at three levels of verbosity](image)

The interface for this prototype supported three levels of verbosity for routing instructions as illustrated in Figure 6. In the high-level option, the user is guided at the hallway intersection level until he/she gets to the final hallway, at which point a count of doors along the way to the destination is given. The intermediate level adds step-by-step directions along with a count of
doors along the whole route. The low level adds additional landmarks and contextual information about the environment. The interface also used vibration patterns to provide tactile feedback. The navigation menu allowed the user to perform tasks such as specifying the destination, getting route directions, and exiting the application. On-screen gestures were used to instruct the tool to repeat an instruction, go back to the previous instruction or repeat all instructions.

Since we do not envision technology solutions completely eliminating the need for seeking human assistance in the future, it is important to design tools in a manner that enables B/VI users to seek assistance from available sources when needed. For example, a graphical map view on the dynamic guidance tool enables sighted bystanders to provide assistance to the B/VI traveler more easily since the bystander can simply click on the relevant location on the map to indicate a place of interest. We are also exploring other ways in which the NavPal tools can more effectively enable B/VI users to seek assistance when necessary.

5. **Annotating Maps and Sharing Information**

For longer-term usefulness and sustainability, it is important to enable B/VI travelers to influence maps both on a personal basis (annotations) and in a public manner (to share information and advocate for changes). To explore these topics we did some initial enhancements to our NavPal dynamic guidance tool and experimented with an initial crowdsourcing app as shown in Figure 7.

First, we added landmark and obstacle input options to the NavPal dynamic guidance tool. In the initial prototype, the “landmark” option allowed the user to annotate the “current” location on the map with a text or audio label for a landmark. The “obstacle” option allowed the user to add obstacles to the map that would be recognized by the route planner in future iterations. This option allows the user to specify the object’s location, its direction relative to the user’s locations, and its width and height in feet by choosing one of three options:
• **Here**: Choosing this option directs the interface to retrieve the current location. The user then is forwarded to the directions menu to specify the object’s direction relative to the user’s position. Then the user gets to specify the width and height of the object.

• **Remote relative**: This option can be useful if the user is made aware of, or detects an object from a distance and can estimate the relative distance to it. As in the previous option, the user then is forwarded to specify direction, width, and height of the object.

• **Remote absolute**: This option allows a user to directly insert an object at a specific absolute location in the global coordinate frame. As in the previous two options, the user then gets to specify direction, width, and height of the object.

For numerical inputs such as width and location coordinates, a modified version of the “Talking Dialer” was used. The Talking Dialer is a free Android application that has a virtual number pad. Wherever the user puts his/her finger on the screen, the number 5 appears and the rest of the numbers are spread relative to number 5. The user feels a vibration and hears a buzz as he/she transitions between the numbers. When the intended number is reached, the user lifts his/her finger off the screen. This action selects the number, speaks it out loud, and prints it on the screen. Shaking the phone deletes the last number in the list of selected numbers. To confirm input, the user clicks the trackball twice. The first click speaks out loud what the user entered to double check with the user that this is correct. Then the second click confirms the entry. The Talking Dialer was modified for NavPal in several ways. First, the dialing ability was disabled. Second, the instructions were modified to reflect the new use context. Third, the application confirmed each value entered by the user.
Towards the goal of sharing relevant information, we also explored an initial crowdsourcing approach for coarse indoor mapping of Wi-Fi signal strengths in buildings. Since a significant percentage of the adult population in the US now owns a smartphone, crowdsourcing indoor localization information can be a viable option. Moreover, since crowdsourcing does not require any costly infrastructure installation, it is also an affordable solution. We implemented a simple mobile application that displays a map interface showing the floor-plan of the current location of the user. The study participants were asked to mark their location on the map as they traversed the building. Each time a point was marked on the map, the mobile application recorded the coordinates of the point on the map along with details of all the Wi-Fi access points (APs) detected by the phone at that location. Each of these points along with their associated Wi-Fi data can be used as indoor landmarks. Through the crowdsourcing, a database of indoor Wi-Fi landmarks was created which was then used to localize test points.

Each entry in the database is represented in the form of a vector. Each element in the vector represents the RSSI of a detected AP and the detected APs are considered in the same order for each point so that they can be compared. A non-zero element indicates that the corresponding AP was detected by the Wi-Fi scan at that point on the map and the value of the element is the RSSI of
that AP. A zero element indicates that a particular AP was not detected. Each of these vectors has corresponding “real” coordinates (ground-truth) on the map that was input by participants via crowdsourcing. To localize a point during a test run, the vector of the point is compared with the vector corresponding to each point in the database to find the most similar database entry. This comparison is done by calculating Euclidean distances between the vector representing the test point and each vector representing points in the database set.

6. Conclusions and Design Guidelines

Our research in assistive technology over the past few years has explored avenues to enhance the safety and independence of B/VI people navigating indoor urban environments. Our work began with a smartphone application designed to provide dynamic localization and path planning assistance to this community, and evolved to address the more complete needs of the B/VI community in the area of indoor navigation and wayfinding. In this report we have described a roadmap for our research in this area along with the specific tools (collectively named NavPal) we have designed to date in each segment of this roadmap. We conclude this report with a set of ten design guidelines we have discerned from this work to date which will be informative to other researchers working in the area of assistive navigation technology for B/VI users.

1. Include users in the design process: The most important guideline for effective work in this area is to include B/VI users and O&M specialists in an iterative design and testing process. Testing conducted with blindfolded sighted users does not yield the same result.

2. Keep the user in the loop: It is important to appreciate the orientation and mobility training of the B/VI users. Navigation assistance tools that keep the B/VI user in the loop and incorporate their input effectively will produce more robust and useful guidance.

3. Pay attention to affordability: Employment and purchasing power can be low among the
B/VI community so assistive tools must be affordable in order to be useful.

4. **Reliability is extremely important**: Because the failure of these tools could jeopardize the safety of B/VI users, the tools must operate reliably to gain the trust of the users. Reliability can be addressed practically by predictable behavior in all scenarios, and graceful degradation in difficult environments. If users can predict failure conditions and how the tool will respond to these conditions, users can detect these situations and be prepared to overcome these limitations of the technology.

5. **Build practical tools**: It is important to ensure that B/VI users will be able to learn to use the technology in a reasonable timeframe, and that the usage scenario of the tool is practical. For example, practical considerations such as theft of expensive technology or the inability of a user to carry and use many/heavy/poorly shaped devices must be taken into account when designing these tools.

6. **Do not overwhelm the user**: Because the B/VI users must pay attention to their surroundings and keep track of a variety of things when navigating, it is important to design assistive tools that do not overwhelm or monopolize the attention of the user. Interfaces should be as simple as possible and allow for customization since the user will often need to multitask, and will want different levels of assistance from the assistive device depending on the specific scenario.

7. **Environmental considerations are important**: In areas with high levels of competing sound, B/VI users often prefer less information from assistive tools so that they can focus on other inputs from the surroundings. In contrast, when navigating through a large empty space, the user may want much more detailed instructions. Furthermore, when a tool provides information that is read aloud, it is important to consider privacy issues and
whether this output is generating distracting levels of background noise.

8. **Expect and adapt to dynamics:** Effective assistive tools will provide mechanisms for recognizing changes in the environment and adapt to those changes in a timely manner that is beneficial to the B/VI user. Distinctions should be made between temporary changes and permanent infrastructural changes for optimal performance.

9. **Make the most of existing resources:** Understanding how B/VI users navigate without technology, and employing universal design principals to harness resources useful to sighted people can contribute significantly to the success of assistive tools for the B/VI community.

10. **Understand the bigger picture:** Understanding procedures, policies, and laws relevant to accessibility can significantly contribute to successful design decisions for assistive tools.

**Acknowledgments**

Many individuals and organizations supported the work presented in this report. Preparation of this report was supported by the US Department of Transportation University Transportation Center Program, Google, Inc., Boeing, Carnegie Mellon University’s Berkman Faculty Development Fund, the National Science Foundation under NSF-NRI Award Number 1317989, and the National Institute on Disability and Rehabilitation Research under the RERC-APT (grant number H133E080019). Any opinions, findings, and conclusions or recommendations expressed in this material are those of the author and do not necessarily reflect the views of the sponsors. Partner involvement has been essential for this work and we were fortunate to collaborate with several groups who have supported various aspects of this project. Colleagues from the Blind and Vision Rehabilitation Services of Pittsburgh (BVRSP) and Western Pennsylvania School for Blind
Children (WPSBC) have provided guidance on this work and have encouraged their networks to participate in our needs assessment and testing. Dr. George J. Zimmerman from the Vision Studies Program at the University of Pittsburgh provided invaluable insight into the field of Orientation and Mobility which also significantly impacted this work.

The author also thanks the many members of the research team who assisted with different aspects of this work; notably, Dr. Balajee Kannan, Hend Gedawy, Nisarg Kothari, Evan Glasgow, M. Freddie Dias, Sarah Belousov, Ermine Teves, Dr. David Kosbie, Daniel Muller, Vansi Vallabhaneni, Zhiyu Wang, Paul Davis, Justin Greet, Maxime Bury, Dr. M. Beatrice Dias, Dr. Yonina Cooper, Syed Ali Hashim Moosavi, Anna Kasunic, Alekhya Jonnalagedda, Ming Wu, Lucy Pei, Satish Ravishankar, Dr. Gary Giger, Sam Jian Yu Li, Hannah Flaherty, and Dr. Aaron Steinfeld.

References

