NavCog: A Navigational Cognitive Assistant for the Blind

Dragan Ahmetovic
Carnegie Mellon University
5000 Forbes Avenue
Pittsburgh, PA 15213, USA
dragan1@cmu.edu

Cole Gleason
Carnegie Mellon University
5000 Forbes Avenue
Pittsburgh, PA 15213, USA
cgleason@cs.cmu.edu

Chengxiong Ruan
Carnegie Mellon University
5000 Forbes Avenue
Pittsburgh, PA 15213, USA
cruan@andrew.cmu.edu

Kris Kitani
Carnegie Mellon University
5000 Forbes Avenue
Pittsburgh, PA 15213, USA
kkitani@cs.cmu.edu

Hironobu Takagi
IBM Research
5-6-52 Toyosu,Koto-ku
Tokyo, 135-8511 Japan
TAKAGIH@jp.ibm.com

Chieko Asakawa
IBM Research
5-6-52 Toyosu,Koto-ku
Tokyo, 135-8511 Japan
CHIE@jp.ibm.com

ABSTRACT

Turn-by-turn navigation is a useful paradigm for assisting people with visual impairments during mobility as it reduces the cognitive load of having to simultaneously sense, localize and plan. To realize such a system, it is necessary to be able to automatically localize the user with sufficient accuracy, provide timely and efficient instructions and have the ability to easily deploy the system to new spaces.

We propose a smartphone-based system that provides turn-by-turn navigation assistance based on accurate real-time localization over large spaces. In addition to basic navigation capabilities, our system also informs the user about nearby points-of-interest (POI) and accessibility issues (e.g., stairs ahead). After deploying the system on a university campus across several indoor and outdoor areas, we evaluated it with six blind subjects and showed that our system is capable of guiding visually impaired users in complex and unfamiliar environments.

CCS Concepts

•**Information systems → Global positioning systems;** •**Human-centered computing → Accessibility technologies;** Auditory feedback; •**Social and professional topics → Assistive technologies; People with disabilities;** •**Networks** → *Sensor networks;*

Keywords

Assistive technologies, Bluetooth low-energy beacons, Turn-by-turn navigation, Navigation assistance, Visual impairments, Localization, Real world accessibility

1. INTRODUCTION

Many blind people are capable of independently traversing familiar routes. This task relies on their capability to craft a detailed cognitive map of the environment through prolonged exploration, and often, through training with Orientation and Mobility (O&M) professionals [5]. For new or rarely visited places, when there is no time to explore the area in advance, independent travel can be quite challenging.

Without a prior knowledge of the environment, it can be difficult for a blind person to find the shortest (or safest) route to a destination. Physical cues that indicate probable paths or points-of-interest in an environment are often purely visual (*e.g.*, signs or landmarks in the distance) and thus inaccessible for the blind. It is often necessary to seek help from a passerby to find an accessible route, but there is of course no guarantee that someone may be available to provide assistance at all times.

A variety of assistive technologies have been studied to help people with visual impairments during navigation in unfamiliar environments [15, 2, 26]. Existing solutions, however, often require long and extensive renovations to the environment. Other solutions also rely on custom proprietary devices that can be expensive or cumbersome [29, 7, 17].

While rough estimates (*i.e.*, errors greater than a few meters) of a users proximity to a POI can be helpful [3, 18, 30], we argue that a higher level of precision is required for giving turn-by-turn directions, especially when guiding a blind person through complex indoor/outdoor environments. For example, when distinguishing between a set of adjacent doors or corridors, a localization error of several meters can result in choosing the wrong path.

We propose **NavCog**, a smartphone-based turn-by-turn navigation system for blind users (Figure 1). The system makes use of a network of Bluetooth low energy (BLE) beacons to localize the user with an approach based on the K-nearest neighbor (KNN) algorithm [25].

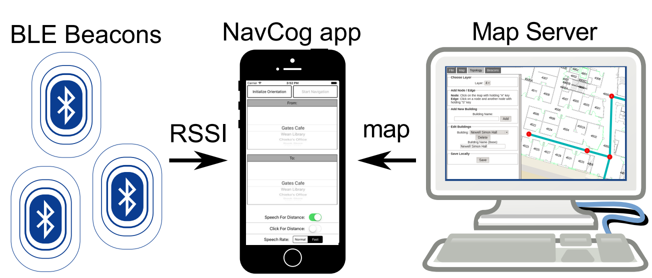

Figure 1: The components of the NavCog system: BLE beacons, Map Server, and the NavCog app

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The advantages of BLE beacons are many: 1) they allow **NavCog** to localize the user more precisely than with GPS or WiFi-based localization methods, 2) they are also easy to install and maintain without requiring extensive renovations to the environment or expensive and cumbersome proprietary hardware, and 3) they are also growing in popularity, and becoming a common sight in public and private environments. The diffusion of BLE beacons will allow us in future to rely on beacons that have been already installed in the environment for other purposes, instead of having to deploy new ones.

To avoid overwhelming the user with cognitively demanding messages, NavCog uses simple sounds and verbal cues as navigation instructions, and the user can interact with the software through a simplified touch interface. In addition to basic navigation, the system can also inform users about nearby POI and possible accessibility issues. While the interaction is currently tuned for blind users, as a future work we will also study high contrast visual interfaces for partially sighted users and visual interfaces for sighted users. Indeed, sighted users can also benefit from NavCog assistance in unfamiliar environments.

A set of tools is also provided for deploying the system in a new environment efficiently and to reduce the workload of expanding the mapped area to new navigation routes. A map authoring tool can create and expand customizable maps that are downloaded by NavCog and used to guide the user through the environment. The evaluation of the localization accuracy shows that NavCog is indeed capable of provide accurate turn-by-turn navigation assistance, without requiring a high workload during the set-up of the system. Evaluations with blind subjects show that NavCog is capable of effectively guiding people with visual impairments through indoor and outdoor environments and the interviews with participants indicate that they are satisfied with the core turn-by-turn navigation capabilities of the system.

2. RELATED WORK

The technological evolution of mobile devices has recently allowed the development of systems to assist visually impaired users during both outdoor and indoor navigation. Outdoor localization and navigation systems commonly rely on GPS positioning [23, 29, 3, 28, 20]. Some approaches, like iMove [12], and BlindSquare [6], assist visually impaired users in exploring POI present in the surrounding environment. While these approaches have not been proposed as navigation systems, in practice they are helpful for people with visual impairments in exploring and creating mental maps of a new area. The GPS signal, however, is often too weak in indoor environments, and even outdoors the GPS localization error can be up to tens of meters [24].

Indoor and outdoor localization techniques that do not rely on GPS often involve structural modifications to the environment by adding after-market assistive technology. One of the first and most widespread navigation assistance tools for people with visual impairments is tactile paving, introduced in 1965 in Japan by Seiichi Miyake [21]. Tactile pavings are integrated in the floors of an environment so that people with visual impairments can follow the pattern on the pavement with their white cane.

Nakajima et al. [26] suggest to use Visible Light Communication (VLC) technology to transmit position information with a VLC-augmented LED light to a mobile device camera, which is then used to localize the user. Few solutions [15, 7, 2] rely on RFID tags installed in the pavement and detected with a white cane augmented with an RFID reader or with RFID readers on user's body. Differently from these solutions, BLE beacons used in our approach are temporarily applied to the environment with velcro stickers, and they can be removed quickly without permanent alterations to the surroundings.

Approaches that do not require structural modifications to the environment rely on existing infrastructure, user's sensing capabilities, smartphone, or other wearable add-ons. Drishti [29] improves GPS localization accuracy up to 0.5m, under clear sky and far from obstacles, with specialized backpack-worn gps sensor. Active RFID tags applied to the environment have also been used to localize a person carrying a RFID reader connected to a personal digital assistant [19]. The approach also includes a wearable module consisting in an electronic compass and a distance sensor in order to provide orientation information and obstacle avoidance.

While the information provided by specialized hardware can be useful, custom devices are avoided in our approach since they can be expensive and cumbersome. Also, since our solution does not mean to replace but to supplement the user's existing mobility tools, such as white canes or guide dogs, functionalities such as obstacle avoidance in user's immediate surroundings [19], are not considered as a goal of this work.

Methods using existing Wi-Fi signals detected by the users's phone to estimate its position [18] also exist. However, the distribution of Wi-Fi access points in the environment is tuned for signal coverage, and not for yielding a good localization accuracy at key points, like intersections. It is also possible to leverage the smartphones' inertial motion unit (IMU) sensors for estimating the user's position based on previous movement (dead reckoning) [13]. The quality of the localization through dead reckoning degrades with time, so Navatar asks users to confirm their location through haptic exploration of surrounding landmarks. In absence of identifiable landmarks (*e.g.*, empty corridors of an office building), this approach is more difficult to use.

Computer vision techniques that use the video camera on the smartphone for sensing the environment have also been proposed. Headlock [17] uses head-mounted Google Glasses to detect doorways and guide the user towards them. Previous works also propose to use smartphone camera and IMU data jointly to localize crosswalks [1] and pedestrian traffic lights [22], and assist blind users during road crossing. These approaches have no knowledge on the absolute position of the detected objects in the environment, and thus they cannot be used for providing general navigation assistance. An absolute positioning approach uses uniquely identified visual tags, detected with the smartphone's camera, to localize the user in the environment [8]. The localization depends on the positioning of the tags with respect to the user and it suffers from occlusion in crowded environments.

Bluetooth low-energy (BLE) beacons have been used to localize users in general purpose navigation (*e.g.*, [31, 9]). To the best of our knowledge, only one other work incorporates BLE beacons techology for the assistive navigation of people with visual impairments [11]. The solution performs localization through multilateration [31, 9], i.e., it estimates the distance of the user from each nearby BLE beacon using the beacons' Received Signal Strength Indication (RSSI). Given the distance information and the position of the beacons, this approach can compute an estimated position of the user.

Conversely, our approach relies of "fingerprints" of RSSI of surrounding BLE beacons across the environment to localize a NavCog-enabled device by comparing its RSSI readings at any given moment with previously gathered fingerprints. We adopt this technique as it has been shown in previous literature to yield a higher localization accuracy, of about 1.5m [14, 27, 33]. Our approach also relies on touch screen input instead of voice recognition since it can be challenging during navigation in noisy environments.

3. THE NAVCOG SYSTEM

This section introduces our technical approaches, the NavCog system and steps to expand navigation routes. The structure of the NavCog system revolves around the interaction between three key components:

1. **Map Server**. The map server stores the information describing each environment and the models required to correctly localize the user in those environments. Maps can be created easily through a web interface and the NavCog enabled mobile devices contacts the server once to download the map (Section *Building the Map*).

2. **Beacon Localization**. Bluetooth beacons installed in the target environment periodically broadcast their identifier to nearby NavCog-enabled smartphones. The aggregated signal information from multiple Bluetooth beacons is used to localize the smartphone inside the environment (Section *Beacon Localization*).

3. **NavCog App**. The NavCog iOS application guides the user to a destination based on a downloaded map and the position of the user obtained through Bluetooth beacons (Section *User Interface*).

3.1 Building the Map

NavCog requires that a map of the environment is prepared before being able to provide navigation assistance. This offline process is performed after installing the beacons and it is done by administrators who wish to make their venue accessible using NavCog. The map serves to 1) build the internal graph structure used for navigation, 2) embed information about POIs, and 3) visualize the installed locations of the beacons. While the beacon locations are not currently used for localization, this information is used for management of beacons, and it will be considered for localization purposes in future (see Section 3.2).

Map Creation.

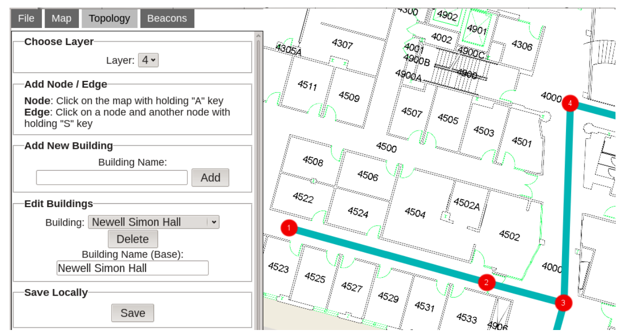
The first step towards building a map consists in uploading a floor plan of the environment (i.e., an image that depicts the location of walls and doors) to the map server. Using a web-based map editor (shown in Figure 2) a developer can easily mark beacons, walkable areas, decision points and POIs. The map editing software also allows the developer to update existing maps with ease during expansions of mapped areas. Once created, the map is uploaded to a remote server and fetched by the NavCog app on user's smartphone. After a map has been downloaded, the position computation is entirely performed on the mobile device – without needing to contact any remote server. This approach allows the NavCog app to localize the user without requiring a local or Internet network connection and without having to share the user's position with any external server.

It is also possible for the users to create, download and share custom maps of private environments directly on their device, without relying on an external server.

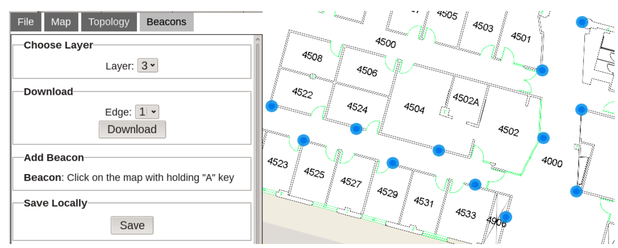
Graph Representation.

Internally, NavCog reduces the structure of the physical space into a graph (green lines and red dots in Figure 2) $G = [V, E]$. A node (vertex) in the graph, $v \in V$ are important locations in the map. Paths (edges) between nodes, $e \in E$ represent walkable areas. An orientation function stores the angle between two adjacent edges $\theta = f_{\text{angl}}(e_i, e_j)$ which is used later to give precise turning directions at navigation time. A description function returns a test description $t = f_{\text{desc}}(e_i)$, encoding information about the path (e.g., a poster about X to the left). At any time step, we can represent the position of the user as a scalar value $x = d(e_i)$, indicating the 'progress' made over an edge. In essence, we are projecting all possible 2D paths connecting two locations onto a straight 1D path. This representation suits the turn-by-turn navigation paradigm as it provides a set of straight edges which can be traversed with a simple walk-and-turn procedure. This approach is also fast to query yet sufficiently accurate for navigation.

In areas that cannot be represented as one dimensional paths, such as unconstrained open areas without any reference system (e.g., no walls or curbs to follow), a user may veer away from the intended path [32]. As a future work, we will investigate how to tailor a navigation field to combine our proposed approach with 2-d localization methods by considering the needs of each portion of the environment.



(a) Path editing: nodes (red dots) and paths (blue lines).



(b) Beacons editing: blue dots mark the beacons.

Figure 2: Map creation interface

Every node $v \in V$ can be: 1) a *destination* node, from and towards which the users can navigate with the NavCog app, 2) a *transition* node that models the change from one floor or area to another, such as elevators, stairs or doors, or 3) a *normal* node. In case of transition nodes, the information on how to reach the next required node is also recorded. For example, if the user has to take the elevator to the second floor, that information will be read to the user once the node is reached. A node or a path can also include information of interest that when reaching accessibility information that may be useful to navigate around the node (*e.g.*, "careful, there is a pole in the middle of the road").

3.2 Beacon Localization

Once the environment map has been defined (i.e., graph structure, beacon locations, POI information), it is the role of the NavCog localization engine to determine the precise location of the user. In order to localize the user, we must first model the transformation between BLE beacon signals and positions in the environment. The following procedure allows us to achieve an accurate localization while requiring a limited workload for the model training.

In the model training stage, we sample BLE beacon signals at known positions using a "fingerprint" based method, similar to those used in previous works [18, 27, 33, 14]. We gather the RSSI fingerprint $\boldsymbol{s}$ (a vector of which the dimensions is equal to the number of beacons) along each portion of an edge e at fixed distances. At each known fingerprint location $\{x\}$ on the path e we collect a fixed number of RSSI samples $\{\boldsymbol{s}\}$. The level of localization accuracy depends on the number of beacons, fingerprint distances, and number of samples per fingerprint location. A long, simple segment with no intersections might need only a few beacons and samples, as there are few chances for mistakes.

Since there is a significant workload associated to the collection of the RSSI samples, in Section 4 we show how the localization accuracy varies by changing the number of RSSI samples collected for each fingerprint location. As a future work, we will also evaluate how the number of sampling points and the number of beacons influence the localization accuracy.

We use this data to train a fast variant of the classic K-nearest neighbor (KNN) algorithm [25] to estimate the position of the device by comparing the current RSSI readings with previously gathered RSSI fingerprints. KNN is a well known non-parametric approach [4], especially useful when it is unclear how to define a parametric model for variable regression. We found that the KNN was able to better model the non-linearities in the RSSI signals of the beacons over traditional parametric logarithmic power drop off models.

To localize the user, NavCog takes the device's current RSSI reading $\hat{\boldsymbol{s}}$, the current edge e and calls an edge specific K-d tree data structure M_e to find the K nearest neighbors, $\boldsymbol{S}_e = \{\boldsymbol{s}_1 \cdots \boldsymbol{s}_K\}$ that are most similar to $\hat{\boldsymbol{s}}$. The KNN search also returns the Euclidean distance of each data point from $\hat{\boldsymbol{s}}$, $\boldsymbol{\Delta}_e = \{\delta_1 \cdots \delta_K\}$, and the corresponding positions on the edge $\boldsymbol{X}_e = \{x_1 \cdots x_K\}$.

The estimated position is computed with a density estimate,

$$\hat{x} = \frac{1}{\sum_{k'} \delta_{k'}} \sum_k x_k \delta_k.$$

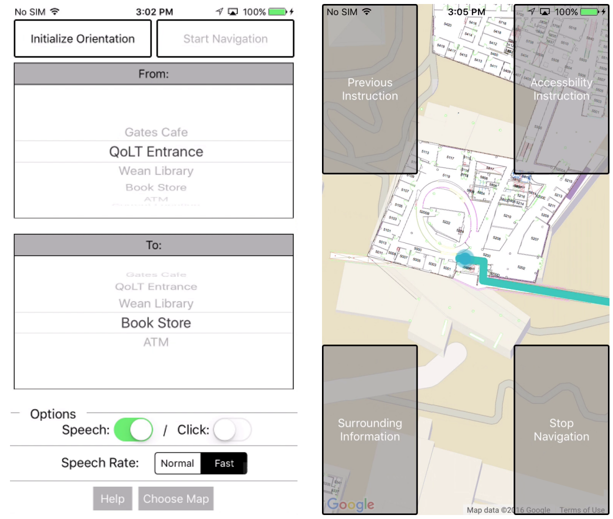
Currently, the RSSI fingerprints of BLE beacons are used to localize the user. As a future work, we will also use the positions of beacons, as defined on the map of the environment, to estimate a likelihood model of the BLE beacons RSSI [16]. This could result in even higher localization accuracy.

3.3 User Interface

NavCog is designed to be able to interact and convey navigation instructions and way-finding information to the user. It can be used in any mapped environment, both indoors and outdoors, since all the information about the surroundings is included in navigation maps that are downloaded independently for each environment. As NavCog is designed for blind users, the main mode of interacting with the user is audio-based. Visual representation of the interface elements is currently used for testing purposes during the deployment and the evaluation of the system. In future extensions, high contrast visual interfaces for partially sighted users will also be considered. NavCog has two screens: 1) the planning interface (Figure 3(a)) and 2) the navigation interface (Figure 3(b)). Both views are designed to have a small number of key elements positioned on the borders of the touch screen in such way that they are easy to find and activate by a person with a visual impairment.

Planning Interface.

The planning interface is used to setup the navigation destination, optional parameters and start the navigation (See Figure 3(a)). This view is divided in 4 areas:



(a) Planning interface (b) Navigation interface

Figure 3: NavCog mobile interface

1. The topmost area contains two buttons. "Initialize Orientation" maps the current orientation of the device with respect to a well known direction. This procedure is needed only when starting the app, from that moment on the direction information is maintained using the rotation information from gyroscope. The orientation of the device is used afterwards to understand when the user is correctly aligned to an edge after a turn. The second button, "Start Navigation" initiates the wayfinding procedure and changes the app to the navigation interface.

2. Immediately under this area, two drop down lists serve the purpose of setting the starting and the ending points of the navigation. These elements cover most of the screen area. It is possible to set the starting and ending points to any of the destination nodes on the map. It is also possible to set the starting point to the current position of the user, (provided that it is on a mapped edge). The route used to guide the user from the starting point to the ending point is computed with the classical Dijkstra's shortest-path algorithm [10] where the cost of each edge is set to that edge's length.

3. The following area is used to set the vocal messages speed (slow speech or fast speech) and the preferred way for receiving distance information: through vocal messages or through sonification. The first approach consists in periodically informing the user about the distance to the next node through synthesized vocal messages (*e.g.*, "20 meters"... "10 meters"... "approaching"). The second approach notifies the user with a repeated clicking sound. The repetition rate is higher the closer the user is to the destination. This approach, while less informative, is less cognitively demanding, which can be preferred in noisy environments.

4. The bottom area of the interface contains two buttons: the first one shows the usage manual for the app while the second one allows to change the current map by choosing one of the ones installed on the device.

Navigation Interface.

The navigation interface (Figure 3(b)) is invoked when the user starts navigating from one point to another. The layout of elements on the screen is designed to simplify the interaction between the blind user and the touch screen. The view contains four buttons positioned in the four corners of the touch screen interface:

1. The bottom right button ("Stop Navigation") is used to terminate the navigation and return to the planning interface.

2. The top left button ("Previous Instruction") repeats the last navigation message that has been conveyed to the user. This is useful if the user was not able to hear the message when it was played, or if the user was not paying attention to the message due to external factors.

3. The top right button ("Accessibility Instruction") is used to query possible accessibility instructions related to the current position of the user (for example, if there is a curb that is easy to trail with a cane).

4. The bottom left button ("Surrounding Information") is used to request additional information about the user's immediate surroundings, such as the description of the current building or area.

The map in the center of the interface, useful for testing of NavCog functionalities, displays the current position of the user as a blue dot and the path the user is traversing as blue lines.

Turn-by-Turn Instructions.

In navigation mode, NavCog can give three types of messages:

1. *Distance announcements* inform the user of the distance to the next action. Two output types are possible. The first periodically informs the user about the distance to the next node through synthesized verbal messages (e.g., "20 meters"... "10 meters"... "approaching"). The second alerts the user with a repeated clicking sound. The speed of the clicking is higher the closer the user is to the destination. Non-verbal sounds, while less informative, require less attention from the user.

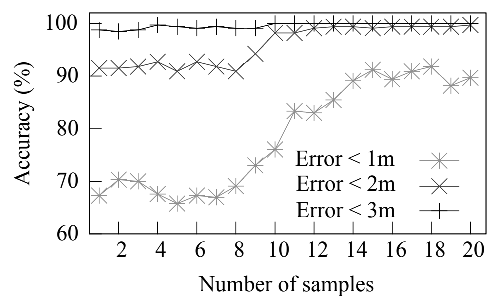
2. *Action instructions* notify the user of the action to perform. They are divided in two categories: 1) turning instructions and 2) transit instructions. Turning instructions tell the user to turn left or right when moving from one path e_i to another e_j. If the turning angle θ is small, the conveyed message is to turn slightly to left or right, as turning too much can lead the user in a wrong direction. Once the user aligns correctly to the new path, based on gyroscope data, a confirmation sound is played. Transit instructions are used when moving between floors or indoor/outdoor areas. The information required to move between floors or buildings depends on the environment layout, therefore it is manually added to the map and read aloud once the user reaches the corresponding transit node. A repeating clicking sound informs the user that NavCog is searching for the user's new location at the associated exit transit node (*e.g.*, the next floor). Once the user reaches that node, the navigation resumes normally.

3. *POI descriptions* are optional audio messages describing POI along the path. These messages are read when the user presses the bottom left button on the navigation interface. A particular type of POI descriptions are accessibility POI. These are used when the user reaches a particularly difficult area to navigate. A vocal message is issued to inform the user that an accessibility information involving their current position is available (message: "Accessibility Notification"). If the user desires to listen to the accessibility notification, it is possible to request it by pressing the top right button on the navigation interface. The last POI type is a destination POI. When the user reaches the destination node, NavCog notifies the user through a vocal message and terminates the navigation (*e.g.*,"The book store is on your right, you have arrived.").

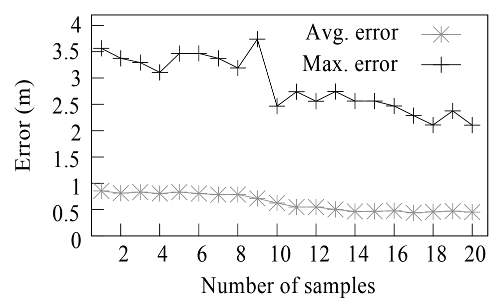
While the current version of NavCog provides only turn-by-turn navigation assistance during the travel, a whole overview of the route could be useful during the planning of the navigation. As a future work, we will also implement a "Route Rehearsal" functionality to allow the users to play the messages corresponding to a navigation path, without actually having to move along the path.

4. LOCALIZATION EVALUATION

We evaluate the accuracy of the NavCog localization module and the relationship between the accuracy and the number of samples gathered at each sampling point. This evaluation allows us to understand how to minimize the sampling effort required during the environment set-up while providing high localization accuracy. In future, we will perform evaluation of other set-up parameters, such as the number of sampling points and the number of beacons. We set up a 16 meter long edge in a 2 meter wide corridor, marked with Kontakt.io [1] Smart Beacons. These beacons are capable of transmitting with a signal strength between -30 dBm to 4 dBm and a transmission interval between 20 ms and 10240 ms.



(a) Localization in 1 m, 2 m, 3 m



(b) Avg. and Max. error

Figure 4: Impact of samples number on localization accuracy

The beacons were positioned with velcro stickers on walls and columns, without permanently modifying the environment. They were placed every meter along the corridor, alternating the side on which they were set, starting from 4 meters before the path and

[1] http://kontakt.io/

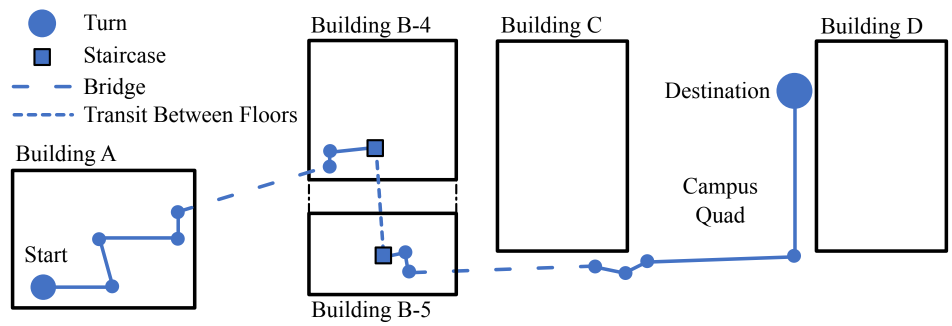


Figure 5: Map of the evaluation field

ending 4 meters after the path. Thus, in total 24 beacons were utilized. We set the transmission strength of beacons to -12 dBm (20 meter range) and the transmission interval was set to 100 ms, to ensure an accurate level of localization. The edge has been marked every 0.5 meters and we gathered 20 RSSI samples for the training of the localization model for each marked point. We collected another 10 RSSI samples for each point to be used as test set.

The evaluation consisted of measuring the localization accuracy for the test set samples in localization models trained with the number of samples used as the fingerprint varying from 1 to 20. We considered two sets of indicators. The first one is the maximum and the average distance errors between the estimated positions of test samples and their actual coordinates. The second set of indicators evaluated the percentage of localizations that fell within 1 meter, 2 meters and 3 meters distance from the samples' actual positions.

We see in Figure 4(a) and in Figure 4(b) that between 11 and 20 samples there is only a minor decrease in localization error, quantifiable in less than 0.20 meters. Under 11 samples the localization error increases steadily, but even with a single sample, the maximum localization error is up to 3.5 meters at most, while the average error increases to only about 0.85 meters. The corresponding accuracy decreases from 89% of test samples localized within 1 meter with 20 samples used during KNN training to 83% accuracy within 1 meter with 11 samples and 67% accuracy within 1 meter with a single sample.

As the default setting for the NavCog environment, based on previous results, we suggest 12 samples per point, corresponding to 2.5 meters maximum error and 0.53 meters average error, and to 83% of test samples localized within 1 meter from their actual positions. This number of samples guarantees a reliable localization accuracy while limiting the sampling workload needed. Note that, on long paths without intersections closer that 5 meters, even the lowest level of accuracy, obtained with a single sample, can still be sufficient.

5. USER EVALUATION

For the purpose of evaluating the capability of the NavCog system to guide people with visual impairments in unfamiliar environments, we performed evaluations with 6 participants on a university campus.

5.1 Evaluation Field

We built the evaluation field on an university campus. The total length of all deployed paths was 530 meters across 21 edges. A training path of 4 edges, with a total length of 73 meters, was used by the participants to become familiar with the system. All the training edges were positioned indoors, with a small rectangular open area, a narrow and long corridor, and an elevator transition before the last edge.

A longer route of 350 meters, spanning over 13 indoor and outdoor edges, was used for the evaluation. The testing path contained a greater variety of areas, covering two buildings, two bridges, a flight of stairs, and the campus quad area (see Figure 5).

The beacons used for the evaluation were two different beacon models, both produced by Kontakt.io. For indoor environments, we used Smart Beacons, which we previously described. For outdoor environments we used Tough Beacons, which guarantee the same performance level, but are also waterproof, shatter resistant, and anti-static.

The beacons were positioned with velcro stickers, as described earlier. They were placed every 4-6 meters, alternating the sides of the hallway or path. We set the transmission strength of beacons to -12 dBm (20 meters range) for most beacons and 4 dBm (70 meters range) on the quad area, where the beacons had to be positioned further apart (about 50 meters and only on one side of the path). The transmission interval was always set to 100 ms, to ensure an accurate level of localization.

5.2 Procedure

We recruited all participants from the city and surrounding suburbs. The campus was not familiar to any participant except P2, who took classes in a nearby building. Once they arrived and consented to the study procedure, we conducted a short interview to collect the demographic information in Table 1.

We also asked the participants about their current navigation strategies to understand where NavCog could assist them. When navigating on outdoor streets, many of the participants already used a GPS system or smartphone application, so they were familiar with turn-by-turn style navigation instructions. Because we were unable to use GPS applications indoors or on outdoor campus areas that were not mapped, it was not feasible to complete a baseline comparison of NavCog against those tools.

Next, the participants were asked to try the NavCog app on two short trips on a training path, which took approximately 5 minutes each. We demonstrated the different features to the participants, including: the notifications of remaining distance, the sound played when a turn is completed, and how to access more information about elevators, stairs, and doors. Because the app was evaluated on an iPhone 6 and integrated tightly with VoiceOver, operation of the app was familiar to 5 of the participants who owned iOS devices. We also showed them the range of accuracy of the system, so they knew how much precision to expect when navigating.

Once the participants were familiar with the navigation system, we asked them to independently navigate on the testing path (to the university bookstore). Both on training and testing routes, the experimenters followed close behind to ensure their safety without interfering in the navigation task.

On the return trip from the bookstore, we asked all participants to walk with a sighted guide as they listened to additional location-based information embedded in the NavCog application. These POIs described nearby items in the environment (trashcans and restrooms), displays of art, historical significance of the bridge and buildings, and additional accessibility information.

After the evaluation, we conducted a longer interview with the participants about their overall impressions and specific design details of the system. We also asked the participants to tell us which types of POIs would be useful or enjoyable to them.

5.3 Video Analysis Evaluation

The video analysis confirms that NavCog is effective at navigating users through mixed indoor and outdoor environments, such as a university campus. The users were unfamiliar with the test environment but, even so, they were able to navigate the environment independently.

In order to gain an understanding of the participants' ability to navigate using the application, two members of the research team viewed and identified six common events in the videos that interrupted navigation:

- **Listened for instructions:** The participant stopped to repeat instructions in the system or asked the experimenters for further instructions.
- **Missed turn:** The participant tried to turn either too early or too late and missed the correct turn area.
- **Over-turn:** When turning, the participant turned more than necessary and lead to incorrect navigation.
- **Veering:** The participant veered to one side enough that it impaired their navigation. This term often applies to white-cane users, although we also used it to describe veering with a guide dog.
- **External factor:** Something external to the participant or system imparied navigation, such as another person on the path.
- **Hit an object:** The participant ran into an object or wall.

The two members of the research team coded each video, and compared their results (Cohen's Kappa, $\kappa = 0.534$). Disagreements were resolved through further review of the videos and discussion until both coders agreed. We present these codes per participant in Table 2 and discuss them in the next section.

6. DISCUSSION

The user evaluations were insightful as they revealed parts of NavCog that needed improvement as well as which features the participants felt were already useful. Because we could not compare against the participants' current GPS applications, we are unable to show how much improvement NavCog would offer to pedestrians on the street. In future work, we would like to evaluate NavCog against two other navigation strategies: tactile maps and oral instructions. Additionally, it would be very useful to construct a highly precise measurement (*e.g.*, with lasers) of the participants' location in an evaluation to understand quantitatively how much they deviated from the path due to inaccuracies in NavCog's localization. Even without a comparison to other strategies, however, the video and interview results are good indicators that NavCog will be useful for navigation.

Table 2 shows the number of navigation errors made during each evaluation by category, and we can see that participants were able to recover from most of these errors (66 out of 76 total) without requiring external assistance. The remaining labeled "Blocking", required assistance from experimenters. Future versions of NavCog should fix these errors as it would improve the user experience and reduce the cognitive demand while navigating, but these improvements are not strictly required to make a functioning navigation aid.

The video data shows that missed turns were a common problem. This issue is encountered when a user turns too early or too late (missed turn) when asked to make a turn. In most cases (21 out of 25), the participants were able to recover from these errors on their own. We noticed that the majority of blocking missed turns (3 out of 4) were encountered just after the campus quad area. This area has a lower localization accuracy due to the fact that a lower number of the beacons was installed and they were positioned only on one side of the path.

One way to address this issue is improving the localization accuracy in the proximity of decision points, such as turns or doors, by increasing the number of beacons in those areas and sampling the RSSI data at a higher resolution. In other areas, such as straight paths with no decision points, the current accuracy level is higher than needed. A future goal of our research will be to understand the relationship between beacon position, sampling resolution, and localization accuracy. Another prospective method to increase the system's localization accuracy and fault tolerance is to integrate dead-reckoning approaches[13] with the beacon approach. These two research directions would help us minimize the number of beacons and the effort needed to deploy the NavCog system in a new environment.

A similar issue to the one presented above arose when participants were asked to make a turn. While the app notified the user when they were facing the correct direction, the users' momentum during rotation often caused them to rotate further than intended (over-turn). This issue was blocking in 3 out of 8 cases. All blocking events were localized on two edges near building *C*. In this case a curved path segment was approximated with a few straight edges to fit our current localization model. This confused users, as they found it difficult to make the small turns necessary to stay on course. By exploring better sonification methods to instruct the user of the correct turn angle, we expect to mitigate this issue in future versions of NavCog.

A feature that participants were very positive about was the ability to repeat a previous instruction if they either were unable to hear it due to ambient noise or were distracted when the instructions was read aloud. Participants sometimes asked for additional information from the app or experimenters while navigating, which indicates that the instructions provided by the system could be more clear. For example, the instructions NavCog gave in the stairwell to get to the next floor were often misunderstood and created 3 blocking events. We will investigate more appropriate ways to convey information to the user with both speech and sonification methods.

During the video analysis we also noted occasions where subjects were interrupted during navigation by obstacles or people in their path (hit object and external). These occurrences did not cause particular discomfort to the users, and in the interviews they were quick to point out that their current navigation aids, such as a white cane or guide dog, were good enough for those types of obstacles. Indeed, the goal of NavCog is not to substitute but to supplement current navigation aids.

Another non blocking event was that the users would occasionally veer in open areas without boundaries to orient themselves [32]. Indeed, a map that approximates paths to straight edges works well in narrow areas, which compose the vast majority of the examined environment. However, open areas (*e.g.*, conference centers or an

ID	Gender	Age	Vision Type	Navigation Aid
P1	M	43	Totally blind, born sighted, progressively lost vision until 18	White cane (primary) and guide dog
P2	F	73	Legally blind from age 6	White cane
P3	F	35	Totally blind from birth	Guide dog (primary) and white cane
P4	F	67	Totally blind from birth	White cane
P5	M	62	Totally blind from birth	White cane
P6	M	66	Totally blind from age 6	White cane

Table 1: Demographic information of our participants.

Code	P1	P2	P3	P4	P5	P6	Blocking
Missed turn	3	3	4	6	2	7	4
Instructions	7	2	2	4	0	2	3
Veering	1	1	1	2	3	4	0
Hit object	3	2	0	3	1	2	0
Over-turn	2	1	0	2	2	1	3
External	1	1	0	1	0	0	0

Table 2: Navigation events encountered by participants in the study.

outdoor plaza) do not fit that approximation. We will need to update our localization and map model to support the areas that don't fit the straight path approximation while still retaining a high level of accuracy.

Participants were not concerned by the precision of the localization, but did request that the application let them know if they made a mistake and help them recover quickly. NavCog does not currently provide any way to indicate to the user if they are going the wrong way, so this is a feature that could be added in future work. In the same vein, most participants mentioned having a "preview mode" to prepare themselves before starting navigation. This is a feature most participants used when navigating with GPS applications, as it helped them prepare for complicated parts of the route.

Finally, the points of interest that we presented to the participants garnered a lot of comments, and the usefulness of the information was dependant on both the person and task. For example, P4 was interested in knowing about an arts display of dresses in a nearby window, but P6 was not interested in information that was not related to navigation. Some participants suggested a filtering mechanism to toggle categories of points of interest on and off, or a way to indicate to the system if they were in a rush or just taking a leisurely stroll.

7. CONCLUSION

We proposed a smartphone mobility aid designed to assist people with visual impairments while navigating in unfamiliar environments. In addition to providing navigation assistance, our system can also convey information about nearby points of interest and possible accessibility hazards during navigation. We designed and implemented a localization algorithm to balance accuracy and deployment workload of the system, an interaction technique based on customizable voice and non-vocal sound instructions, and tools to accelerate the deployment process.

We deployed the navigation system on a university campus across several indoor and outdoor areas, and evaluated it with six visually impaired subjects. The interviews with participants indicate that NavCog still lacks some features they expect from a commercial navigation application, but they all expressed that the core turn-by-turn paradigm was something they would use.

Based on the evaluation of the localization accuracy and on the analysis of the videos we conclude that our localization technique is robust, the system is able to effectively guide the user in unknown environments, and it can be deployed in new areas with a reasonable workload. We will continue to work on improvements to our approach to increase the localization accuracy, reduce user confusion, and make the entire system easier to deploy and maintain.

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