NavCog3: An Evaluation of a Smartphone-Based Blind Indoor Navigation Assistant with Semantic Features in a Large-Scale Environment

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ABSTRACT

Navigating in unfamiliar environments is challenging for most people, especially for individuals with visual impairments. While many personal navigation tools have been proposed to enable independent indoor navigation, they have insufficient accuracy (e.g., 5–10 *m*), do not provide semantic features about surroundings (e.g., doorways, shops, etc.), and may require specialized devices to function. Moreover, the deployment of many systems is often only evaluated in constrained scenarios, which may not precisely reflect the performance in the real world. Therefore, we have designed and implemented NavCog3, a smartphone-based indoor navigation assistant that has been evaluated in a 21,000 m^2 shopping mall. In addition to turn-by-turn instructions, it provides information on landmarks (e.g., tactile paving) and points of interests nearby. We first conducted a controlled study with 10 visually impaired users to assess localization accuracy and the perceived usefulness of semantic features. To understand the usability of the app in a real-world setting, we then conducted another study with 43 participants with visual impairments where they could freely navigate in the shopping mall using NavCog3. Our findings suggest that NavCog3 can open a new opportunity for users with visual impairments to independently find and visit large and complex places with confidence.

CCS Concepts

• **Human-centered computing~Accessibility technologies;** • **Social and professional topics~People with disabilities;** • Information systems~Location based services

Keywords

Indoor navigation; visual impairments; points of interest; voice-based interaction; user evaluation

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Figure 1. A participant (P5) using NavCog3 heading to a movie theater from a station during Route 1 in Study 1. The smartphone was worn to free the participant's hands while walking.

1. INTRODUCTION

Navigating large, unfamiliar environments in the real-world is a challenging task for people with visual impairments. While sighted individuals can visually obtain semantic information such as doorways, stairs, and shop information to aid navigation, people with visual impairments must rely on non-visual senses [13] or request assistance from another person, who might not be readily available [35]. To facilitate independent mobility for people with visual impairments, many assistive navigation systems have been proposed (see survey by Fallah *et al.* [18]). While much progress has been made towards building prototype systems, many systems have not been deployed at scale in realistic scenarios.

Towards real-world adoption in large environments such as shopping malls, hospitals and airports, we hypothesize that current technologies need to be improved by: (1) achieving more accurate localization to enable more precise instructions, (2) providing non-visual semantic features of the surroundings to help with navigation, and (3) utilizing common devices that are already available to the general public. Many existing indoor navigation systems do not have sufficient accuracy where errors in localization can range from 5 to 10 *m* [4], and do not provide semantic features, which can be extremely useful for orientation and mobility [26, 35]. Moreover, existing systems often require specialized devices for users to carry (e.g., [23, 36]), which may not be practical. Due in part to these key issues, indoor navigation systems have not been successfully deployed nor evaluated in a large-scale environment to meet the needs of people with visual impairments.

On the basis of the hypotheses mentioned above, we will address the following research questions: (1) What level of accuracy can we achieve for indoor navigation, and is it sufficient for turn-by-turn navigation? (2) What are the needs, preferences and expected use cases for accessing semantic features during navigation? (3) To what extent can a navigation system be used to enhance orientation and mobility of individuals with visual impairments?

With the ultimate goal of large-scale adoption in real-world environments, we have designed a smartphone-based navigational assistant for people who are blind or have visual impairments, called **NavCog3**. NavCog3 is based on the initial work of Ahmetovic *et al.* [9, 10], which was only validated in a controlled setting at a university building. Our system uses a similar indoor localization approach using a Bluetooth Low Energy (BLE) beacons network. However, the interface and underlying system architecture is entirely different. It is designed to support people with visual impairment in large-scale indoor environments with semantic features including nearby points of interest (POIs) such as shops and restaurants as well as non-visual landmarks (e.g., doorways).

To address our research questions, we first deployed the system at a large shopping mall (approximately 21,000 m^2), for the evaluation. Finally, we conducted a controlled study with 10 participants with visual impairments consisting three fixed route navigation tasks using NavCog3 (see Figure 1). Lastly, we conducted another user study with a more realistic scenario where we asked 43 participants with visual impairments to use NavCog3 for any destination inside the mall to reflect on natural usages in a large-scale environment.

We measured the localization accuracy while participants were performing navigation tasks for the first study, and the average accuracy was 1.65 *m*, which is comparable to one of the best accuracies achieved by a smartphone-based indoor localization system [3]. With this accuracy, 93.8% of the 260 turns made by participants were successful. We further assessed the turn performance and found that 45° turns were more difficult to make than 90° ones. Findings from the first study confirmed that participants found semantic features to be useful for boosting their spatial awareness (e.g., obstacles), orientation, and mobility (e.g., using elevators). Findings from the second study showed that NavCog3 could enable our participants to reach the shops of their choice, which has not been well supported in other localization systems. These findings suggest that NavCog3 can increase users' confidence in walking independently as well as the opportunities to find and visit new places.

2. RELATED WORK

Our research largely builds on previous work in indoor navigation for people with visual impairments. We were also informed about landmarks and POIs, as well as studies on mobile interactions on-the-go.

2.1 Indoor Navigation and Localization

For safe and independent navigation, many people with visual impairments receive orientation and mobility (O&M) training. However, navigating in an environment can still be challenging as they have to rely on non-visual cues [13]. While commercial navigation tools are often used (e.g., Google Maps[1], Ariadne[2]), these GPS-based navigation systems are limited to outdoor environments only. Thus, many researchers have studied various approaches to support indoor localization for a general purpose [40] as well as for blind navigation [18, 20, 31]. Various localization approaches were explored such as infrared, ultrasound, RFID, lasers and ultra-wideband (UWB) sensors [3, 19, 23, 36]. While these techniques are promising and have sub-meter accuracy, they usually require users to carry a dedicated device (i.e., a receiver).

Approaches that do not require additional devices, other than a smartphone or a sensor installation in a physical environment, include Wi-Fi [15], Bluetooth [29], inertial measurement unit (IMU) sensors [17], a camera [32], or a combination of multiple sensors [24]. While camera-based approaches have the potential for supporting the so called "last meter" problem [30] as they can collect rich visual information about a scene [24, 32], these are not robust enough for a limited field of view and various lighting conditions, which is particularly more problematic for blind users [8]. Although NavCog3 requires the installation of sensors, it does not require additional devices other than a smartphone, is free from line of sight, and can estimate users' location with high accuracy (1.65*m* on average). NavCog3 can provide indoor localization with high accuracy to support reliable navigation assistance for people with visual impairments using built-in IMU sensors in smartphones and Bluetooth Low Energy (BLE) beacons, which are also used in large-scale field studies [5, 6, 28].

2.2 Landmarks and Points of Interest

Both landmarks and POIs can be useful for confirming a person's current location/orientation and understanding the environment while travelling [26, 34]. However, it is difficult for people with visual impairments to be aware of what is around them compared to those without visual impairments who can examine their surrounding at a glance. In this regard, some researchers studied types of semantic features that can be helpful during navigation, particularly for pedestrians with visual impairments [16, 26, 34]. For example, Dias *et al.* [16] interviewed 20 people with visual impairments, and the majority of the participants reported using environmental clues (e.g., smells, sounds) or landmarks (e.g., doorways, elevators) for indoor navigation and orientation. Similarly, Kammoun *et al.* [26] classified semantic features into POIs (e.g., buildings, shops) and landmarks (e.g., ground texture, traffic light) for outdoor environments. In terms of POI information, there are commercial mobile applications that provide POI such as iMove[3] and BlindSquare[4]. BlindSquare, for instance, informs a user of nearby POIs with categories such as education, shopping, and transportation on the basis of the nearest Bluetooth beacon from the user. However, it does not provide turn-by-turn navigation for indoor environment. To the best of our knowledge, NavCog3 is unique as it not only determines if these semantic features are nearby, but also provides their positions and orientations, which is difficult to achieve without accurate localization.

2.3 Interaction On-The-Go

Although the possession of mobile devices is found to increase the independence of mobile contexts for users with visual impairments [27], interacting with mobile devices while walking on a street is difficult as they need to stay alert to ensure their safety [2, 41]. Moreover, since their hands are often occupied by holding a cane or a leash for a guide dog, using a mobile phone is even more challenging unless one-handed or hands-free interaction is supported. [33]. To support hands-free navigation for people with visual impairments, many researchers have focused on wearable technologies [37, 38]. However, these approaches require a custom device, which may not be feasible to support a large population without mass production. In this regard, NavCog3 has been designed as

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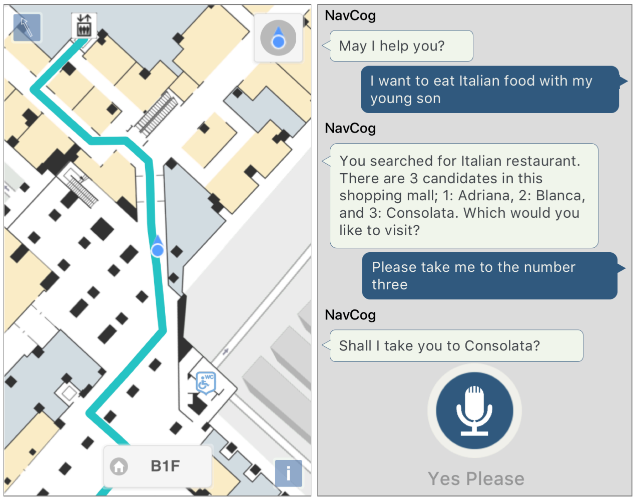
[1] https://maps.google.com

[2] https://www.ariadnegps.eu

[3] http://www.everywaretechnologies.com/apps/imove

[4] http://www.blindsquare.com



NavCog
May I help you?
I want to eat Italian food with my young son
NavCog
You searched for Italian restaurant. There are 3 candidates in this shopping mall; 1: Adriana, 2: Blanca, and 3: Consolata. Which would you like to visit?
Please take me to the number three
NavCog
Shall I take you to Consolata?

(a) Navigation (b) Conversation

Figure 2. Example screen-shots of NavCog3's interfaces.

a smartphone application to be more readily accessible for users in need. In addition, to minimize the cognitive load, we have added a conversation-based cognitive assistant to NavCog3, which is widely used in many applications such as those for elderly care [22] and knowledge workers [12]. Although evaluating this cognitive assistant is not within the scope of this paper as it is in its early development phase, we expect that speech-based input will relieve cognitive and physical loads, as speech input is known to be faster than manual input [11].

3. THE DESIGN OF NAVCOG3

NavCog3 is a smartphone-based indoor navigation system for people with visual impairments. As a smartphone app, it is readily available to any smartphone user who wishes to get navigational assistance without the need for an additional device. In this section, we describe the navigation instructions and modes of interactions. The details of our implementation can be found in Section 4.

3.1 Navigation

NavCog3 provides turn-by-turn instructions and immediate feedback when incorrect orientation is detected. While speech is used as the our primary feedback for the instructions accessible to people with visual impairments and to enable eyes-free interaction, the system also displays navigation information on the screen (e.g., planned route, current location) to support users who wish to receive visual feedback (see Figure 2a).

3.1.1 Turn-By-Turn Instructions

With the advantage of higher accuracy, NavCog3 can provide turn instructions in a timely manner so that a user with visual impairments can easily make correct turns without visual aid. In addition, it provides "Approaching" notifications prior to the turning point to allow prepare users get prepared. After a turn (or at the start point), the system informs the user of the distance from the current position to the next point and the action that they have to take, either when turning or transitioning between floors (elevator, escalator, or stairs). For sufficiently long distances ($\leq 15\ m$), the system gives a verbal update on the remaining distance every 15 *m*.

At each turning point, the system provides verbal instructions to convey the angle of the turn: a *slight turn* ($22.5° < \theta \leq 60°$), a *regular turn* ($60° < \theta \leq 120°$) and a *big turn* ($120° < \theta$). When a user reaches a turning point, both a short vibration and a short sound effect are provided simultaneously to instruct the user to start turning. Once the user reaches the correct heading, the feedback is provided again to instruct him/her to stop turning and continue walking.

Table 1. Categories of semantic features for NavCog3.

	Main	**Sub**	**Information Provided**
Landmark	Pathways	Floor	Tactile paving, ramp, step, slope
		Door	Types of doorway (e.g., automatic)
		Obstacles	Existence of object (e.g., trash cans)
	Floor Transition	Elevator	Call button locations, control panel location inside the elevator, Braille button availability, audible announcement availability, wheelchair accessibility
		Escalator	The correct standing side (left or right), directions to adjacent escalator(s)
		Stairs	Shape (e.g., straight, u-shape), number of steps and landings
POI	Shopping and Food	Shop	Type of shops, name
		Restaurant	Cuisine, name
	Facility/ Utility	Restroom	Gender, wheelchair accessibility
		Other	ATM, information center

To help users get back on track when they veer from a planned route (by 6 meters), or head in a wrong direction (by 120 degrees), our system provides failure-safe verbal guidance. For example, when a user is walking in the opposite direction, the system would say, "Turn around. You might be going in the wrong direction." If a faster route exists from the user's current location after deviating from the original route, corrective guidance would lead them to the new route accordingly.

3.1.2 Nearby Landmarks and POIs

The system provides information about nearby landmarks and POIs so that a user can walk comfortably and confidently. The types of semantic features supported by our system are described in Table 1, which have been recategorized by summarizing previously examined features in [16, 26, 34]. We define landmarks as features that can provide physical or tactile cues to help users to confirm their location such as tactile paving, doorways, and other building infrastructures (e.g. elevator, escalator, and stairs). POIs, such as shops and facilities (e.g., restroom), are defined as places that might interest users during navigation.

In general, information about POIs and landmarks is provided when a user is within proximity to them. However, information about accessibility-related landmarks is already included in the navigation instructions, for example, "Proceed 14 meters on *tactile paving* and turn right at *the end of the corridor*."

3.2 Interactions

3.2.1 Search POI via Conversation

For unfamiliar environments, users may not know what places are available for them to navigate. To help users decide their target destination, NavCog3 enables users to explore nearby POIs by asking the cognitive assistant via speech input. The assistant provides recommendations on the basis of user's request with descriptions. As shown in Figure 2b, a user can initiate a conversation with a request such as "I want to eat Italian food with my young son". The system then provides a set of recommendations on the basis

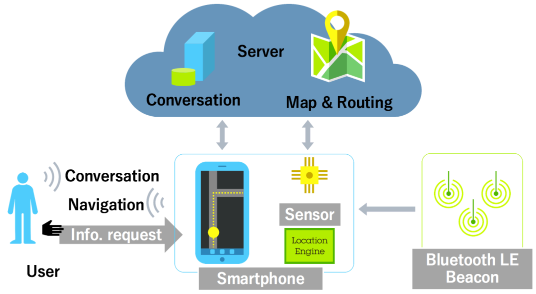


Figure 3. An overview of the system: A user requests navigation or surrounding information via speech-based interaction using a smartphone.

of the search conditions extracted from the users' input; "Italian" and "kids are accepted", in this case. The system also enables users to either manually search for the destination from a POI list or set the destination using speech input if she/he has a specific place in mind.

3.2.2 On-demand Instructions

NavCog3 supports on-demand instructions, which enables users to listen to the current instruction again upon request by simply tapping the screen or pressing a control button on a headset as needed. Example instances include confirming the next action, confirming the surrounding information (e.g., the position of elevator buttons), or checking the remaining distance to the next turning point. The system generates an appropriate instruction on the basis of the current navigation status, user's location, and user's heading.

4. IMPLEMENTATION

In this section, we present the main components implemented for the NavCog3 system (see Figure 3) as well as the deployment process in a large-scale environment with our own evaluation field as an example.

4.1 System Components

4.1.1 Location Engine

We use a hybrid localization technique with a particle filter that combines BLE beacon fingerprinting and pedestrian dead reckoning (PDR), which has been developed as a library component of an open source project[5]. The PDR component uses a filter to recover the delay caused by the smoothing of BLE beacon's RSSI. As a result, using the component to track a user's heading and movement makes the localization responsive and stable. To achieve higher accuracy with the component, proper beacon placement and fine-grained fingerprinting of beacon signals are essential.

Beacon Placement. We first need to place beacons in the environment where we wish to support navigation assistance since the localization is estimated on the basis of detectable beacon signals and their received strength from a user's phone. To achieve high accuracy, the beacon placement interval should be about 7–10 *m* based on our experience. In addition, the ideal height of the beacon is between 2 and 3.5 *m* for better radio wave signal reachability; the interference from people passing by is weaker at higher positions, thus, signals with less noise can be received. However, if the position is too high, the accuracy decreases because the variance of the signal power increases as the distance between a device and the beacons increases. Beacons can be hidden if the covering material has little impact on the signal power.

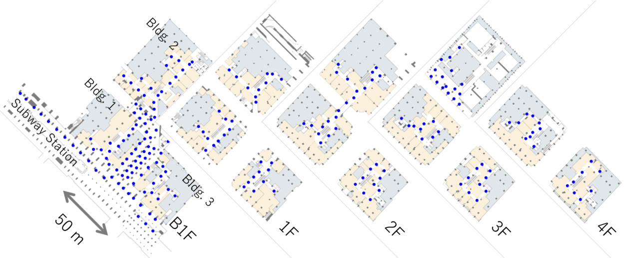


Figure 4. Beacon deployment locations in the environment. Blue dots indicate beacon locations.

Fingerprint Collection. Once all the beacons are placed, fingerprint samples, which are vectors of RSSIs from all beacons within a range of a known location, are collected. Fine-grained fingerprinting is required for accurate location estimation. However, it is time-consuming to manually collect fingerprints point-by-point, and existing alternatives do not guarantee high accuracy [25]. So, we have developed a fingerprinting machine with a LIDAR sensor that can scan the environment with lasers and obtain its coordinates in the environment with an error of centimeter-level. This approach can reduce the radio map creation time by 1/20 compared to that of the point-by-point manual fingerprinting method.

4.1.2 Map & Routing Server

The map data model is an extension a spatial network specification for people with disabilities [1]. It converts a list of physical pedestrian maps and semantic features described in Section 3.1.2 into a spatial graph with semantic features. Each graph edge has attributes detailing path width, gradient, steps, stairs, elevator, escalator, and tactile paving. The routing service computes the optimum route from the available routes given the current location and the destination as well as users' mobility preferences. By default, it avoids escalators and includes routes with tactile paving for users with visual impairments. NavCog3 generates navigation instructions on the basis of these routes and semantic features along them.

4.1.3 Conversation Server

A conversation system has been developed as a Web service that combines two different types of components: (1) a basic conversation script utilizing Watson Conversation API[6] for fixed common facilities and (2) a shop recommendation engine for the shops that can be replaced after a certain period of time. Users' speech input is transcribed using the speech framework of iOS[7] and then submitted to the server. The server runs both components simultaneously and returns the recommendation result if the confidence level of the result is greater than a certain value, otherwise, it returns the result of the conversation script. For shop recommendations, the system requires shop information in text format with annotations such as shop name, shop introduction, opening hours, food menu, and so on. The recommendation engine tries to extract the search conditions from the query text to filter shops that meet the conditions, and then match text in the query with the text in the shop information.

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[5] https://github.com/hulop/

[6] https://www.ibm.com/watson/developercloud/conversation.html

[7] https://developer.apple.com/reference/speech

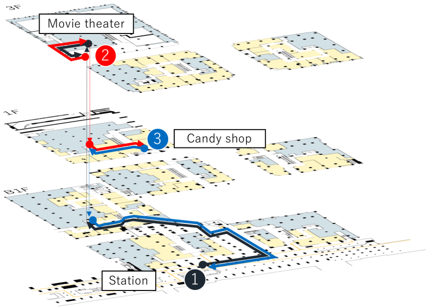

Figure 5. The visualization of three routes for Study 1 in the order of presentation: 1) a station to a movie theater (177*m*), 2) the theater to a candy shop (54 *m*), and 3) the shop to a subway station (176 *m*). Each route included a transition between floors via an elevator.

4.2 Large-Scale Deployment

The deployment area was a shopping mall with three buildings spanning about 21,000 m^2, which is connected to an entrance of a subway station on the first basement level as shown in the Figure 4. The mobile app was built as an iOS app distributed from Apple's App Store[8], which provides indoor localization to the entire deployment area and enables users to navigate to about 100 shops in the shopping mall.

To support indoor navigation for this environment, we first created indoor floor plans for the area from CAD drawings of the building. We then compiled the pedestrian network and POIs for the entire shopping mall from scratch using a map editor. We also collected and annotated text information of the shops from the Webpages of the shopping mall to train the recommendation engine of the cognitive assistant.

In addition, we deployed approximately 220 battery-powered BLE beacons[9] inside the shopping mall, with each costing about $20 and lasting for about one year. Most of the beacons were hidden; placed upon a ceiling while the rest were placed close to the floor if the ceiling was too high in places. The beacon locations are shown as blue dots in Figure 4. All beacons were deployed over two nights during closing hours. Due to ownership issues, we did not deploy beacons inside shop areas, although this would be helpful to navigate users right to the front of the entrance of each shop when it is selected as a destination.

As we used a LIDAR sensor, we were able to collect fingerprints for the map creation of the entire area in 12 hours (three hours for three buildings and corridors on the first basement level). This fingerprint collection was conducted during shop opening hours because the signal strength from beacons can change depending on the environmental changes over time, such as closed shutters. We have also collected approximately 8,000 data points while moving to evaluate the localization error prior to the user study, and the result was 1.47 *m* on average.

5. STUDY 1: FIXED ROUTE

To evaluate the localization accuracy of NavCog3 and to collect subjective feedback on the usefulness of semantic features during navigation, we conducted a 90-minute single-session study with 10 participants with visual impairments. During the study, participants were asked to navigate three fixed routes in a large-shopping mall.

Table 2. Participants' demographic information for Study 1.

PID	Gender	Age	Visual Impairments	Mobility Aid
P1	Female	42	20/2000 for both eyes	White cane
P2	Female	46	20/500 with right eye only	White cane
P3	Male	54	Totally blind	White cane
P4	Female	44	Totally blind	Guide dog
P5	Male	33	Totally blind	White cane
P6	Female	53	20/500 with left eye only	White cane
P7	Male	38	Totally blind	White cane
P8	Female	40	Totally blind	White cane
P9	Male	42	20/500 with left eye only	White cane
P10	Female	48	Totally blind	White cane

5.1 Method

5.1.1 Participants

We recruited 10 participants with visual impairments via a local Braille library (Table 2). Six were totally blind (P2 and P10 were visually impaired since birth), and the rest had low vision (at best 20/500). In terms of smartphone ownership, all but three participants (P7-P9) have used smartphones for at least over a year except for one (P4) had used a smartphone for a week. Four of the participants (P3, P5, P8, P10) reported that they have used a navigation system such as Google Maps before. All have participated in a study with the previous version of NavCog except three participants (P5, P6, P10). Participants were compensated ¥10,000 (approximately $90) for their time.

5.1.2 Apparatus

All participants used a revised version of the NavCog app during the study session. The app was running on an iPhone 6 smartphone, and bone conduction headphones were used to provide audio instructions while not impeding any environmental sounds, which is found to be important for safe navigation [2, 41]. All participants were asked to wear a waist bag with the phone attached to free their hands from holding the phone during navigation, which again is important when walking on a street, especially for users with visual impairments whose hand is often occupied for holding a cane [2, 41]. All participants were provided with a remote control to interact with NavCog3 while the phone was secured in the bag. The app logged every event with a time stamp while the app was running (e.g., instructions), and an experimenter followed and videotaped all participants with a 360-degree camera right behind them.

5.1.3 Procedure

The session began with a background questionnaire. A short training session (5–10 minutes) was then given to the participants who were trying NavCog3 for the first time until they were familiar with the system, such as the navigation voice and the types of information and instructions the system provides during navigation. Prior to the tasks, participants were asked to walk for 5–10 *m* to calibrate their location and heading. They were then asked to navigate three different routes in a shopping mall as shown in Figure 5. The order of the routes was the same for all participants. We instructed the participants to walk normally at their own pace, and the volume and speech rate were adjusted for each participant prior to the tasks. After the task was completed, we collected subjective responses on the usefulness of the semantic features we provided during navigation.

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[8] https://itunes.apple.com/app/navcog/id1042163426?mt=8

[9] http://business.aplix.co.jp/product/mybeacon/mb004ac/

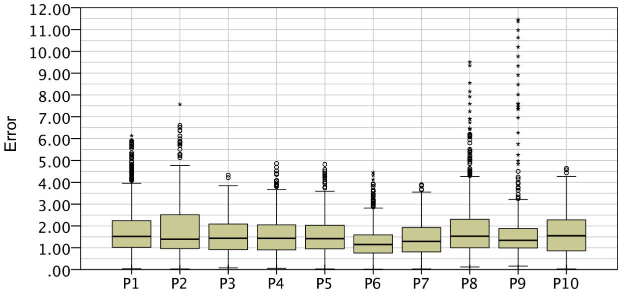

Figure 6. The localization error in meters per participant across three routes (lower value indicates higher accuracy). The boxes indicate 25%, 50% and 75% percentiles. The outliers that do not fall in either 1.5 or 3 times the interquartile range (IQ) from the upper box are shown as circles and asterisks, respectively.

5.1.4 *Data Analysis*

We visually annotated participants' actual location every second, except for when they were inside an elevator, from the video data for 26 turns per participant. We also annotated their turn performance (i.e., whether they successfully made a turn without the experimenter's help), which varied in terms of turning angle (16 regular, 10 slight turns), and width of a corridor after making a correct turn (M=3.21 *m*; SD = 1.37 *m*; range 1.0–7.3 *m*). We used paired t-test and Chi-square tests for independence throughout the analysis. We also collected audio recordings of participants' comments. The comments were transcribed, translated from Japanese to English, and analyzed on the basis of themes of interest following [14] (e.g., landmark, cognitive load).

5.2 Findings

All ten participants were able to complete the navigation tasks for all three routes. On average, the total task completion time was 990.5 *s* (SD = 129.1), and the total travel distance was 450.0 *m* (SD = 32.4) for all three routes per participant.

5.2.1 *Overall Localization Accuracy*

The overall localization accuracy of NavCog3 was evaluated in terms of the Euclidian distance between a user's actual location and estimated location. We extracted 7641 actual location points across the three routes from the participants' results. The average error rate was 1.65 *m* (SD = 1.13), which is comparable to the 1.47 *m* accuracy, measured offline prior to Study 1. It is also a better result than that of a former study (1.70 *m*) in a relatively small space (670 m^2) [29]. The localization accuracy per participant is shown in Figure 6. Some participants had higher errors than others (P2, P8, and P9) due to issues with the localization engine. One issue was that the engine stopped working, due to a problem, during navigation while the user kept walking (P9). Another issue was that the heading estimation failed inside an elevator (P2 route 2 and P8 route 1).

5.2.2 *Navigation Performance*

As our system provides turn-by-turn navigation instructions, we further examined the video data to analyze navigation errors, focusing on participants' turn performance: *success* if they were able to make the turns without requiring help from the experimenter, *fail* if otherwise. Of the 260 turns in total, 221 turns were successful on the first attempt. Of the 39 missed turns, 22 were successful on the second attempt. An experimenter had to interrupt participants for the remaining 17 turns to prevent participants from entering shops (N=8), bumping into people (N=2), because the participant seemed lost (N=2), or due to system-related issues (N=5). In terms of the turn success rate, the average rate per participant across all routes was 85.0% (SD = 10.6%) without any correction, and 93.5% (SD = 5.8%) either with the help of the system's failure-safe guidance (N=18) or by participants themselves (N=4); the average success rate with or without correction was significantly different with the paired t-test (t_9 = -2.43, p = .038). The distribution of localization accuracy with turn performance (*success* vs. *fail*) is shown in Figure 7, where each turn is grouped on the basis of its localization accuracy with an interval of 0.5 *m* (e.g., [0.0, 0.5), [0.5, 1)). We further examined a number of variables that might have affected the turn success rate, focusing on turn angle (regular turn at 90° *vs.* slight turn at 45°) and width of the passage.

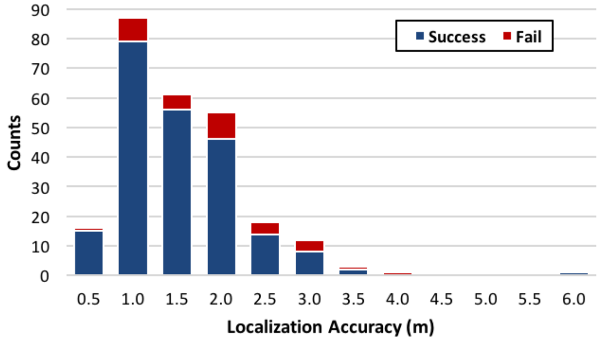

Figure 7. The distribution of localization accuracy in meters (N = 254). Note that x-axis indicates the start of each interval. For example, 0.5 refers to the interval of [0, 0.5).

Turn Angle. Although the average passage width and localization accuracy were not significantly different between the types of turns (*regular* vs. *slight*), a Chi-square test for independence revealed that the turn types significantly impact the turn success rates; $\chi^2_{(1)}$ = 6.245; p = .012; φ = .155. While 89.4% of regular turns were successful, only 78.0% were successful for slight turns, suggesting that regular turns are easier than slight turns. For example, P4 stated that there was no problems when turning 90 degrees, but it was difficult to ask her dog to make slight left turns.

Width of passage. We hypothesized that the turn success rate would be lower as the width of the turn gets narrower. While we were not able to find a correlation between the success rate and the width, some participants commented that making a correct turn is more difficult for narrow widths. For example, P3 mentioned that he would miss the timing of the turn when the corner was narrow due to the width of the corridor being narrow. However, even if he turned into a wide passage too much, he could correct himself later.

5.2.3 *Feedback on Semantic Features*

Confirming prior findings that surrounding landmarks and POIs are useful for people with visual impairments [26], all participants reacted positively to the semantic features we provided during the navigation, especially for non-visual and silent landmarks such as elevators.

Tactile Paving and Obstacles. All participants considered tactile paving on the floor to be useful except for P4, a guide dog user. She commented that since she walked with a dog, she did not care about tactile paving. The trend was similar for obstacles; eight participants reported that this information was useful for safety. Again, P4, who relies on her guide dog for avoiding obstacles, did not consider this information to be useful.

Elevators. We also provided information on the location of elevators as well as their button locations both inside and outside of them. While one participant (P9), who reported that he tends to rely on his sight whenever he can, did not considered this information to be useful, elevator-related information was appreciated by the rest of the participants. P8, for example, commented that, because elevators these days are mostly silent, she wishes to be notified when the door is open since she does not know whether the elevator is open or closed unless she notices that people are getting on and off.

Points of Interest. All participants considered POIs information to be useful. We noticed that some participants considered POIs would increase the enjoyment of walking places (N=4). P10, for example, stated that without NavCog3 she would have never walked into an interesting shop to buy something unless somehow encouraged to do so, and that it was a pleasure to enjoy shopping from the information received. P7 also wished to use POIs information to enhance his spatial awareness. To be specific, he said that the information on nearby shops and vending machine locations were informative as a clue for large crowds (e.g., people coming out from shops, standing in line, etc.) so he can be more cautious.

While POIs may increase the joy of walking around and improve spatial awareness, two participants specified that they would like to receive POI information only upon request or have two modes of navigation such as *exploration mode* where a user can receive detailed information about nearby POIs and *direction-only mode*, which does not provide POI information at all.

Suggested Semantic Features. Besides the information about the existence and location of obstacles, four participants also wished to know the types of obstacles and the distance from them so that they can decide whether they should be alert or not. For example, P10 wished to get more descriptive information, followed by an action suggestion, stating that when told by NavCog3 that there was an obstacle on the right side, because she could not feel it, she was not sure if she had to walk carefully or differently from how she had been. On the other hand, P4, who travels with a guide dog, did not consider the distance information to be useful. Instead, she was more interested in learning about specific directions to the available target so that she can instruct her dog to walk towards it, such as a door or stairs.

Above all, the most commonly suggested landmarks were stairs and escalators, which participants considered to be more accessible than elevators when transitioning between floors (N=7). P8 stated that she did not like the elevator because of other people. It would be difficult to determine when to ride the elevator, when the door was open, and whether the floor buttons could be touched or not. She preferred not to use an elevator when alone, even if there was voice guidance, choosing to take the escalator when possible.

5.2.4 Overall Experience

The overall feedback was very positive for all participants. Most or all of the participants considered the timing of the guidance was appropriate (N=9), the instructions were easy to understand (N=10). In addition, nine participants reported that they would be able to walk alone in any unfamiliar place with NavCog3. Furthermore, all participants expressed their desire to use our system for navigating other places. Here, we summarize the factors that might have influenced the overall experience with NavCog3.

Spatial Mapping. As found in [26], seven participants reported that semantic features helped them to understand the spatial layout of the environment as well as their orientation. For example, P3 mentioned that if he can recall the location from the name of a shop, it would be useful as a reference to other locations (e.g., "next to OO store"). P5 also commented, *"While walking on tactile paving, [NavCog3] taught me the location of a stop, and the name of a shop on the street. So, whether you are going out or returning, you can figure out where you are going by drawing a map inside your head."*

Cognitive Load and Safety. While semantic features may help with spatial understanding of the environment, seven participants reported that this information required extra cognitive load during navigation, which also introduced safety concerns. P6 mentioned that *"If I become distracted by the system announcements, I cannot be aware of the surroundings. Therefore, I cannot avoid obstacles as I can usually do."* P8 also reported that she only needs to listen to the guidance announcements with about 70–80% focus, so that she can concentrate on surrounding sounds and other people. On the other hand, P2 commented that she feels safer using NavCog3 as she felt like she can see the environment as she passes by semantic features using NavCog3. She said that the verbal description of the surroundings makes her feel like she can see the scenery, which reduces her fear while walking.

Hands-Free Interaction. As the needs for hands-free interaction in mobile contexts was found to be important in prior studies for pedestrians with visual impairments [2, 41], half of the participants expressed that they appreciate NavCog3 for enabling hands-free use. P2 said that it was easier to move because she did not have to hold the phone in her hand and could concentrate on using her white cane. P9 specified that he preferred to put the phone in a pocket, especially when in elevators, as it is difficult to find and press the button while holding a phone. Interestingly, while they appreciated the hands-free feature, two participants mentioned that they would rather not use this feature because it requires additional devices, a remote control and a headset in this case, other than the phone (P1), or to feel the haptic feedback better (P8).

6. STUDY 2: FREE ROUTE

To investigate the usability of NavCog3 for supporting large-scale environments and to identify and confirm users' needs for indoor navigation reflecting on their natural usages, we conducted a second study where participants were asked to use NavCog3 for any destination of their choice in a large shopping mall.

6.1 Method

6.1.1 Participants

Forty-three participants (22 males, 21 females) with visual impairments via a local Braille library volunteered for the study. The participants were almost equally split between people who were totally blind (N=21) and people with low vision (N=22). For the blind user group (**B**), 18 participants used a white cane and three had a guide dog. For the low vision group(**LV**), 17 were cane walkers, two had a guide dog, and three did not use any mobility aid. We did not collect their age or smartphone ownership for this study.

6.1.2 Apparatus

Apparatus was almost the same as the user study. All participants used the same version of NavCog3 as in the user study on an iPhone 6 smartphone. Again, bone conduction headphones were used to convey audio feedback. Unlike the participants in Study 1 who were asked to wear the phone in a waist bag, participants were allowed to carry the phone however they like. For participants who wished to keep their phone in their pocket or a bag, we provided a remote control as an option. The app logged every event with a time stamp while the app was running. No video was recorded for any sessions in Study 2.

6.1.3 Procedure

We had three sessions in parallel, and an experimenter accompanied each participant to ensure their safety. The duration of a session was up to 60 minutes. After a brief explanation on how to use the app at the beginning, participants could freely select the destinations of their choice using the conversational interface. Unlike Study 1, no training was given to any participant. All participants were asked to navigate to at least three different destinations using NavCog3. At the end, we gave short questionnaires and had wrap-up interviews with the participants.

6.1.4 Data Analysis

We audio-recorded participants' comments, which were later transcribed and translated for further analysis. Comments were analyzed on the basis of themes of interest in Study 1 as well as new emergent themes, again following [14]. We also collected usage logs for 188 itineraries from the participants during the study, which includes the distance, duration, and selected destinations. The selected destinations were diverse; of over 100 POIs inside the shopping mall, 52 POIs (47 shops, 5 facilities) were selected at least once. The average travel distance was 152 *m* (*SD*=90.4) and the average travel duration per trip was approximately five minutes (*M*=305 *s*; *SD*=177 *s*).

6.2 Findings

Although no instructions were given to participants to demonstrate the full potential of our system, participants' overall reaction was very positive. Because most of the questions asked in the questionnaire were open-ended, the responses were counted in terms of the number of participants who mentioned it during the wrap-up interview.

6.2.1 Feedback on Semantic Features

Landmarks of Interest. When asked about the perceived usefulness of landmark information (scaled from 1 to 5, where 5 is the best), the majority of the participants showed a positive attitude by giving ratings higher than 3 (*N*=31 out of 43), as confirmed in Study 11wq1. Reflecting Study 1's findings, some participants found some landmarks to be more or less useful than other landmarks. For example, a participant (B13) with a guide dog commented that the information on button location was helpful since dogs cannot recognize buttons. On the other hand, LV5 did not considered Braille availability of the buttons in the elevator to be useful because the participant could not read Braille. The suggestions for other landmarks were more diverse. Some wished to know their current location, chairs, stairs, moving objects and crowds (*N*=2 each). The most frequent requests were related to elevators (*N*=7), which was found to be less preferred than stairs and escalators in Study 1. Again, participants wished to be informed of the current floor location (*N*=3), the arrival time (*N*=2), the heading direction (up/down), as well as which elevator has arrived if there are multiple ones (*N*=1 each).

Points of Interest. In addition to seven participants commenting that they liked the nearby POI information as is, a greater number of participants (*N*=10) expressed a different preference (e.g., level of details). Some wanted more concise announcements especially when shops are on both sides (*N*=2), while five participants wished to get more detailed information on shops. For example, LV21 wished to have a "window shopping mode" with more frequent updates on shops nearby. Other participants wished to turn POI information on and off (*N*=2) or did not want this information at all (*N*=1).

6.2.2 Overall Experience

Cognitive Load and Spatial Awareness. We asked participants if the amount of guidance the system provided was appropriate to not cognitively overwhelm them during navigation. While most of them said the amount was appropriate, some participants showed concerns of losing spatial awareness of surroundings (*N*=5), which could lead to safety issues, as found in Study 1. For example, B11 commented that it was impossible to concentrate on the guidance and create a mental map at the same time, and that it may be safer to cut down the amount of guidance so that one can also be aware of themselves. One solution suggested by five participants was to provide a preview so that they could listen to the guidance prior to their itinerary, and focus on the surroundings while walking.

Independent Navigation. As our primary goal is to support people with visual impairments to navigate independently in any unfamiliar environment, we asked participants if they think our app would allow them to walk alone in other places (i.e., *Navigation Confidence*), and 25 participants reported "yes", not just for unfamiliar environments but also for familiar places at different times of the day (in daytime vs. at night). For example, B12 specified that *"I would be able to navigate places without feeling anxious."* Two participants also liked that NavCog3 would allow them to go out immediately without preparation (e.g., scheduling assistance). The places that participants wished to use NavCog3 for independent navigation included large facilities such as stations (*N*=6), shopping malls, universities (*N*=3 each), offices (*N*=2), hospitals, airports, restroom, and even at home (*N*=1 each).

6.2.3 Other Suggestions for Improvement

In terms of distance, three participants mentioned that they would prefer the distance information to be described in number of steps instead of in meters. As for the turns, four participants from Study 2 also commented that making slight turns was difficult, where two of them suggested using clock position. Interestingly, two participants suggested connecting NavCog3 with other services. B12, for example, wished that our app to link with other services such as Google Maps or shop websites.

7. DISCUSSION

On the basis of our findings, we reflected on the implications for supporting large-scale indoor navigation for people with visual impairments.

7.1 Accuracy Requirements

Overall, most participants could successfully complete tasks without any support at our achieved accuracy. The localization error during the user study sessions was 1.65 *m* on average, which is comparable to one of the best accuracies for an indoor navigation system running on an off-the-shelf smartphone [3, 29]. We observed that most of the errors can be corrected by our fail-safe guidance system without improving the accuracy (Section 5.2.2.). This suggests that our localization accuracy may be sufficient for supporting turn-by-turn navigation as a well-designed fail-safe guidance system can complement the current accuracy limitations. However, it is still important to provide high accuracy for finding small targets such as an elevator button, door knob, or water tap (referred to as a last meter problem [30]).

7.2 Landmarks and Points of Interests

The majority of the participants from both studies considered landmarks that our system provided to be useful (Section 5.2.3 and 6.2.1), confirming the importance of surrounding information for pedestrians with visual impairments to aid their orientation and mobility [17, 26]. Information about elevator locations, for example, was appreciated because they are silent, making them difficult to find. Although our information was largely limited to constructed landmarks such as tactile paving on the floor and doorways, some participants commented that non-physical clues such as sounds from an escalator or changes in light was also useful, confirming that individuals with visual impairments use multiple sensory channels to understand the spatial layout of a physical environment [16]. In this regards, it would be useful to encode information on ambient sounds (e.g., escalator operating sounds) and other types of landmarks into the navigation instructions to inform users what clues to look for on the way.

We found that the landmarks and points that participants found *interesting* or *useful* varied in terms of mobility aid and their objective (i.e., exploration *vs.* way-finding), as found in [39]. For example, the information about obstacles or tactile paving may be less appealing for a guide-dog user compared to white-cane users. Thus, the types of semantic features that a user wishes to be informed about should be personalized or customizable like in BlindSquare [7]. This would also be helpful to reduce the amount of information that may result in cognitive overload while walking, which we will discuss further in the next section.

7.3 Augmenting Navigation Aids

Regardless of which primary mobility aid they use, all participants from the user studies wished to use our system as a complementary means of navigation assistance. In contrast, many participants of our study complained about decreased attention to their surroundings due to the attention to the navigation instructions (Section 5.2.4 and 6.2.2.) For wide adoption, however, seamless augmentation of users' existing navigation skills would be important. To avoid impeding users' mobility, cognitive load should be considered when designing a navigation assistant, so that users can keep their routine during their way-finding. For example, the system can provide instructions when a user is standing still then offer as little guidance as possible when walking so as to not impede users' awareness of surroundings. If they can have a spatial layout of the environment in advance, they can focus on their safety, which is one of the major concerns for people with visual impairments [2, 41].

7.4 Support for Large-Scale Environments

We were able to deploy an indoor navigation system in a large-scale environment (Section 4.2). We demonstrated that our localization accuracy is reliable even in a large shopping mall (Section 5.2.1) that has diverse attributes of an indoor environment (e.g., open space, corridors with various width, crowds, etc.). Findings from Study 2 suggested that users were able to select diverse destinations and navigate to their desired POIs successfully (Section 6.1.4). Moreover, they felt confident walking independently in unfamiliar environments (Section 6.2.2). While important, supporting indoor navigation for a large-scale environment is challenging. As well as deployment costs, collecting landmark information for indoor areas is also time-consuming. We plan to investigate various approaches to help reduce costs such as physical crowdsourcing [21] or computer-based automation. We believe that our system is a great example that shows the feasibility of supporting large-scale environments and how our system can enable independent navigation.

7.5 Limitations

Although attempting to capture the natural usage of our system by allowing participants to navigate to any destination of their choice, a longitudinal field study may reveal additional implications for designing navigation system for people with visual impairments. In addition, we did not control participants' exposure to previous versions of our system, which might have affected navigation errors or subjective responses, although we did not any find noticeable differences. Moreover, different results may have been found had we recruited a different population, especially for the findings related to guide-dog users as the sample size was small. For future work, additional studies with a larger number of guide-dog users or other users with various needs (e.g., wheelchair users, foreigners) would be useful.

8. CONCLUSION

We designed and implemented NavCog3, a smartphone-based indoor navigation assistant for pedestrians with visual impairments. Our system is characterized by turn-by-turn navigation with high localization accuracy and semantic features for spatial understanding. We deployed our system in a large shopping mall and evaluated it with over 50 participants to assess the feasibility of supporting indoor navigation for large-scale environments in the real world. Our study findings show that NavCog3 can achieve high accuracy (1.65 *m* error on average). Subjective responses confirmed that semantic features were perceived to be useful for building spatial map of the environment as they navigate. We also showed that with NavCog3, participants were able to find and navigate to any destination of their choice. All these suggest that our system can be adopted to be used in other large indoor environments, and can open the opportunity for users with visual impairments to freely navigate with confidence.

9. REFERENCES

[1] -Draft development specification for spatial network model for - pedestrians. Ministry of Land, Infrastructure, Transport and - Tourism, Japan, 2017. http://www.mlit.go.jp/common/ - 001177505.pdf visited at 2017-05-01. -

[2] -A. Abdolrahmani, R. Kuber, and A. Hurst. An empirical investigation of the situationally-induced impairments experienced by blind mobile device users. In *Proceedings of the 13th Web for All Conference*, page 21. ACM, 2016.

[3] -Microsoft indoor localization competition - IPSN 2016. https://www.microsoft.com/en-us/research/event/microsoft-indoor-localization-competition-ipsn-2016/ visited at 2017-05-01.

[4] -New version of Google Maps brings indoor floor plans to your - phone. http://edition.cnn.com/2011/11/30/tech/mobile/new-version-google-maps-indoors-wired/ visited at 2017-05-01. -

[5] -SFO app for visually impaired navigation by indoo.rs, 2014. - https://indoo.rs/sfo/ visited at 2017-05-01. -

[6] -Wayfinder app helps the blind navigate the tube, 2014. - http://www.wired.co.uk/article/wayfindr-app visited at - 2017-05-01. -

[7] BlindSquare indoor navigation, May 2015. http://blindsquare.com/

indoor/ visited at 2017-05-01.

[8] -D. Adams, L. Morales, and S. Kurniawan. A qualitative study to support a blind photography mobile application. In *Proceedings of the 6th International Conference on PErvasive Technologies Related to Assistive Environments*, page 25. ACM, 2013.

[9] -D. Ahmetovic, C. Gleason, K. M. Kitani, H. Takagi, and C. Asakawa. Navcog: turn-by-turn smartphonenavigation assistant for people with visualimpairments or blindness. In *Proceedings of the Web for All Conference*, page 9. ACM, 2016.

[10] -D. Ahmetovic, M. Masayuki, C. Gleason, E. Brady, H. Takagi, K. Kitani and C. Asakawa. Achieving Practical and Accurate Indoor Navigation for People with Visual Impairments. In *Proceedings of the Web for All Conference*, page 9. ACM, 2017.

[11] -S. Azenkot and N. B. Lee. Exploring the use of speech input by blind people on mobile devices. In *Proceedings of the 15th International ACM SIGACCESS Conference on Computers and Accessibility*, page 11. ACM, 2013.

[12] -P. M. Berry, K. Myers, T. E. Uribe, and N. Yorke-Smith. Task management under change and uncertainty. In *Proceedings of the Workshop on Constraint Solving under Change*, 2005.

[13] -A. Black, J. E. Lovie-Kitchin, R. L. Woods, N. Arnold, J. Byrnes, and J. Murrish. Mobility performance with retinitis pigmentosa. *Clinical and Experimental Optometry*, 80(1):1–12, 1997.

[14] -V. Braun and V. Clarke. Using thematic analysis in psychology. *Qualitative research in psychology*, 3(2):77–101, 2006.

[15] -Y.-C. Cheng, Y. Chawathe, A. LaMarca, and J. Krumm. Accuracy characterization for metropolitan-scale wi-fi localization. In *Proceedings of the 3rd international conference on Mobile systems*, applications, and services, pages 233–245. ACM, 2005.

[16] -M. B. Dias, E. A. Teves, G. J. Zimmerman, H. K. Gedawy, S. M. Belousov, and M. B. Dias. Indoor navigation challenges for visually impaired people. In *Indoor Wayfinding and Navigation*, pages 141–164. CRC Press, 2015.

[17] -N. Fallah, I. Apostolopoulos, K. Bekris, and E. Folmer. The user as a sensor: Navigating users with visual impairments in indoor spaces using tactile landmarks. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*, CHI '12, pages 425–432, 2012. ACM.

[18] -N. Fallah, I. Apostolopoulos, K. Bekris, and E. Folmer. Indoor human navigation systems: A survey. *Interacting with Computers*, page iws010, 2013.

[19] -J. Faria, S. Lopes, H. Fernandes, P. Martins, and J. Barroso. Electronic white cane for blind people navigation assistance. In *World Automation Congress (WAC), 2010*, pages 1–7. IEEE, 2010.

[20] -N. A. Giudice and G. E. Legge. Blind navigation and the role of technology. *The Engineering Handbook of Smart Technology for Aging, Disability, and Independence*, pages 479–500, 2008.

[21] -C. Gleason, D. Ahmetovic. (2017) LuzDeploy: A Collective Action System for Installing Navigation Infrastructure for Blind People. In *Proceedings of International Web for All Conference*

[22] -S. Helal, C. Giraldo, Y. Kaddoura, C. Lee, H. El Zabadani, and W. Mann. Smart phone based cognitive assistant. In *UbiHealth 2003: The 2nd International Workshop on Ubiquitous Computing for Pervasive Healthcare Applications*, 2003.

[23] -A. Hub, J. Diepstraten, and T. Ertl. Design and development of an indoor navigation and object identification system for the blind. In *ACM Sigaccess Accessibility and Computing*, number 77-78, pages 147–152. ACM, 2004.

[24] -T. Ishihara, J. Vongkulbhisal, K. M. Kitani, and C. Asakawa. Beacon-guided structure from motion for smartphone-based navigation. In *Winter Conference on the Applications of Computer Vision*. IEEE, 2017.

[25] -S. H. Jung, B.-C. Moon, and D. Han. Performance evaluation of radio map construction methods for wi-fi positioning systems. *IEEE Transactions on Intelligent Transportation Systems*, 2016.

[26] -S. Kammoun, F. Dramas, B. Oriolaand, and C. Jouffrais. Route selection algorithm for blind pedestrian. In *Control Automation and Systems (ICCAS), 2010 International Conference on*, pages 2223–2228. IEEE, 2010.

[27] -S. K. Kane, C. Jayant, J. O. Wobbrock, and R. E. Ladner. Freedom to roam: a study of mobile device adoption and accessibility for people with visual and motor disabilities. In *Proceedings of the 11th international ACM SIGACCESS conference on Computers and accessibility*, pages 115–122. ACM, 2009.

[28] -J.-E. Kim, M. Bessho, S. Kobayashi, N. Koshizuka, and K. Sakamura. Navigating visually impaired travelers in a large train station using smartphone and bluetooth low energy. In Proceedings of the 31st Annual ACM Symposium on Applied Computing, pages 604–611. ACM, 2016.

[29] -D. G. Luca and M. Alberto. Towards accurate indoor localization using ibeacons, fingerprinting and particle filtering. In *2016 International Conference on IndoorPositioning and Indoor Navigation (IPIN)*, 2016.

[30] -R. Manduchi and J. M. Coughlan. The last meter: blind visual guidance to a target. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*, pages 3113–3122. ACM, 2014.

[31] -R. Manduchi and J. Coughlan. (computer) vision without sight. *Communications of the ACM*, 55(1):96–104, 2012.

[32] -R. Manduchi, S. Kurniawan, and H. Bagherinia. Blind guidance using mobile computer vision: A usability study. In *Proceedings of the 12th International ACM SIGACCESS Conference on Computers and Accessibility*, ASSETS '10, pages 241–242, 2010. ACM.

[33] -U. Oh and L. Findlater. Design of and subjective response to on-body input for people with visual impairments. In *Proceedings of the 16th international ACM SIGACCESS conference on Computers & accessibility*, pages 115–122. ACM, 2014.

[34] -J. E. Pérez, M. Arrue, M. Kobayashi, H. Takagi, and C. Asakawa. Assessment of semantic taxonomies for blindindoor navigation based on a shopping center use case. In *The 14th International Cross-Disciplinary Conference on Web Accessibility*, W4A 2017. ACM, 2017.

[35] -P.-A. Quinones, T. Greene, R. Yang, and M. Newman. Supporting visually impaired navigation: a needs-finding study. In *CHI'11 Extended Abstracts on Human Factors in Computing Systems*, pages 1645–1650. ACM, 2011.

[36] -L. Ran, S. Helal, and S. Moore. Drishti: an integrated indoor/outdoor blind navigation system and service. In *Pervasive Computing and Communications, 2004. PerCom 2004. Proceedings of the Second IEEE Annual Conference on*, pages 23–30. IEEE, 2004.

[37] -D. A. Ross. Implementing assistive technology on wearable computers. *IEEE Intelligent systems*, 16(3):47–53, 2001.

[38] -R. Velázquez. Wearable assistive devices for the blind. In *Wearable and autonomous biomedical devices and systems for smart environment*, pages 331–349. Springer, 2010.

[39] -M. A. Williams, A. Hurst, and S. K. Kane. Pray before you step out: describing personal and situational blind navigation behaviors. In *Proceedings of the 15th International ACM SIGACCESS Conference on Computers and Accessibility*, page 28. ACM, 2013

[40] -J. Xiao, Z. Zhou, Y. Yi, and L. M. Ni. A survey on wireless indoor localization from the device perspective. *ACM Computing Surveys (CSUR)*, 49(2):25, 2016.

[41] -H. Ye, M. Malu, U. Oh, and L. Findlater. Current and future mobile and wearable device use by people with visual impairments. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*, pages 3123–3132. ACM, 2014.