Navigating Visually Impaired Travelers in a Large Train Station Using Smartphone and Bluetooth Low Energy

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ABSTRACT
People with visual impairments face challenges when navigating indoor environments, such as train stations and shopping malls. Prior approaches either require dedicated hardware that is expensive and bulky or may not be suitable for such complex spaces. This paper aims to propose a practical solution that enables blind travelers to navigate a complex train station independently using a smartphone without the need for any special hardware. Utilizing Bluetooth Low Energy (BLE) technology and a smartphone's built-in compass, we developed *StaNavi* – a navigation system that provides turn-by-turn voice directions inside Tokyo Station, one of the world's busiest train stations, which has more than 400,000 passengers daily. *StaNavi* was iteratively co-designed with blind users to provide features tailored to their needs that include interfaces for one-handed use while walking with a cane and a route overview to provide a picture of the entire journey in advance. It also offers cues that help users orient themselves in convoluted paths or open spaces. A field test with eight blind users demonstrates that all users could reach given destinations in real-life scenarios, showing that our system was effective in a complex and highly crowded environment and has great potential for large-scale deployment.

CCS Concepts
• Information systems → Location based services • Human-centered computing → Accessibility systems and tools

Keywords
Indoor navigation, wayfinding, smartphone, visual impairment, public transit, Bluetooth Low Energy.

1. INTRODUCTION
Individuals who are blind and visually impaired face challenges when traveling to unfamiliar places. For outdoor navigation, GPS-based commercial smartphone apps, such as BlindSquare (http://blindsqure.com) and Ariadne GPS (http://ariadnegps.eu), have been deployed and gained popularity among blind users thanks to built-in accessibility features on mobile devices (e.g., Apple's VoiceOver). However, navigating indoors where GPS is ineffective remains largely unsolved, especially for large and complex public spaces (shopping malls, train stations, airports, etc.) that are a part of our everyday lives. In particular, transportation settings are a critical domain that must be addressed, because public transit, such as subways and trains, plays a key role in the lives of people with visual impairments by offering access to employment, education, shopping, etc.

A number of indoor navigation systems for the visually impaired (VI) have been developed. Typical approaches are based on technologies such as RFID [1, 4, 18] and infrared [8, 9], but they require dedicated hardware. Some systems exploit smartphone sensors [6, 19] – Wi-Fi, inertial sensors, and cameras – without requiring special hardware. However, these systems either suffer from insufficient positioning accuracy or may not be useful in a crowded place. Furthermore, most systems in the literature have been tested in specific routes or places, such as university campuses, have not been thoroughly conducted with intended users, and are lacking in clear evidence from real-life situations [15]. Consequently, no single solution has gained widespread acceptance [17].

Our goal is to propose a practical working solution, especially the design and implementation of a client application, which enables VI to move around independently inside large and complex public buildings, such as train stations and airports, using a readily available positioning technique and modern smartphones without the need for users to carry additional devices. In this paper, we present *StaNavi* – a smartphone-based navigation system for a large train station. The leveraging proximity detection capability of Bluetooth Low Energy (BLE) technology and a smartphone's built-in compass, StaNavi allows blind travelers to determine their current location and obtain turn-by-turn instructions to a destination. We implemented and deployed it at Tokyo Station, one of the busiest train stations in the world, which has more than 400,000 passengers and 3,700 trains per day. Indeed, facilitating a useful and reliable navigation system for VI inside such a large and complex space involved several practical problems, such as fluctuations in proximity and compass readings and factors that reduce VI's sense of orientation commonly found in a train station – high noise levels, bumping into people, large open spaces (e.g., lobbies), etc. [2]. We iteratively designed our system in collaboration with blind users in order to provide features that can enable them to cope with such challenging conditions and reach

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their destinations. These features mainly include: (1) Simple and one-handed user interfaces that can be performed easily by users holding a cane, (2) a route overview that summarizes the total route in terms of the main areas and turns on the route, and (3) navigation cues that describe convoluted paths and open spaces to help VI orient themselves. For example, StaNavi provides spatial relations among objects in a large space around ticket gates – facing south, there are ticket gates in front, stores on the right side, a ticket office on the left side, and a corridor leading to platforms at the back. We also conducted a field test with eight blind users in the context of actual use in day-to-day life, rather than in a carefully controlled environment. Each participant carried out a navigation task four times (the total shortest path length was approximately 600 m), and all of them could reach given destinations, showing that our system was effective in a complex and highly crowded environment.

The rest of this paper is organized as follows. In Section 2, we explore indoor localization techniques and existing systems for aiding blind travelers. In Section 3, we describe the design and implementation of our system in detail. Section 4 presents a field test to verify the usability of our system and its results. In Section 5, we discuss our findings. Finally, Section 6 concludes this paper.

2. RELATED WORK

Many localization techniques have been developed for indoor spaces, and they can be roughly categorized into two categories: infrastructure-free and infrastructure-based. A typical positioning technique that does not rely on infrastructure is dead-reckoning (DR), which utilizes sensors, such as an accelerometer and gyroscope. Another approach is vision-based localization using cameras, where the images are processed to match the pre-collected features of the environment. Infrastructure-based approaches deploy beacons in a physical space. The beacons typically emit wireless signals with unique identifiers that are associated with location information. Such beacon-based technologies include RFID, infrared (IR), Wi-Fi, and BLE. In this research, we employ BLE technology for our system, the most accurate localization method that is currently available on modern smartphones with a low cost ($5 per unit) and low power consumption (runs for years on a coin cell) [20].

Existing systems have employed one or more positioning techniques to assist blind travelers in indoor spaces. Tsirmpas et al. [18] installed passive RFID tags on a floor and developed a wearable module integrating a reader and ultra-sonic finder to detect both tags and obstacles. Alghamdi et al. [1] proposed a smartphone-based indoor navigation system using active RFID technology. Some systems augment a standard white cane with sensors instead of requiring the user to wear devices. Faria et al. [4] attached a RFID reader to the cane so that users could follow a pathway equipped with tags. Guerrero et al. [8] used an IR LED mounted cane and Wii Remotes to localize and guide the user. Jain [9] exploited both IR and DR technologies to direct users inside a building. The waist-worn module detects the IR sensors installed on the wall and sends their locations to a mobile phone. Vision-based approaches have recently attracted much attention [5, 10]. Headlock [5] uses Google Glass to help users lock onto a landmark (e.g. a door) across large open spaces. Joseph et al. [10] integrated a head-mounted camera and waist-worn Kinect to obtain the user environment and used a custom haptic belt to deliver directional instructions. While these systems can achieve accurate navigation, they require dedicated hardware that could be costly and cumbersome to carry. Our system uses smartphones without requiring any additional hardware for users.

Meanwhile, some research efforts have investigated leveraging computing and the sensing capabilities of smartphones without additional external sensors. Spindler et al. [16] developed a smartphone app that offers spatial information and directions in a large airport using Wi-Fi fingerprinting. Flores and Farcy [6] used DR to infer a user's location through step counting, but it suffered from different step lengths due to hesitation in walking. SIMO [7] fuses various sensors on smartphones to locate a user, but it asks the user to point the smartphone in the same direction as the user's body, which is impractical in some situations. Seeing Eye Phone [19] uses smartphone cameras to capture, and transmits images of the environment to a server that calculates the user's position. Navatar [3] employs DR, and to correct DR errors it requires the user to confirm and input landmarks (e.g., hallway intersections and doors) before receiving the next instruction. Although these approaches can work well in relatively uncrowded and confined indoor areas, they may not be useful in large and complex spaces crowded with people. Our system provides several features (described in Section 3) that can be helpful when performing navigation under realistic conditions.

3. THE STANAVI SYSTEM

StaNavi is a BLE-based guidance system that runs on smartphones that allows blind users to obtain their current location, points-of-interest (POIs), and turn-by-turn directions to a destination in Tokyo Station. In the remainder of this section, we present an iterative design process and describe our system and implementation in detail, highlighting the novel features specialized for the intended users.

3.1 Design Process

The current version of StaNavi has been developed via four iterations of implementation, testing, and refinement. During the entire development process, we have collaborated closely with a blind teacher at a special school for VI, and his valuable and practical advice has helped us incrementally refine the overall requirements and functionalities of the system.

The first prototype only provided automatic notification of the user's current location and some relevant information when detecting a beacon in order to identify how blind users experience the BLE-based information service and investigate the feasibility of navigation functionality. Two blind people (one female and one male) – both of whom are not smartphone users and use Tokyo Station five to 10 times a year – tested the prototype in the field for about an hour. They could easily understand the concept of our system and provided comments about the representation of surroundings and importance of knowing the directions they are facing.

Based on our observations and feedback from the initial prototype test, we developed the navigation functionality and consulted the blind teacher. He was generally positive about the functionalities of StaNavi and gave advice on user interfaces and route descriptions for ensuring effective navigation. After refining the prototype, we again asked the blind teacher to thoroughly test our system in the field by thinking aloud while navigating to several

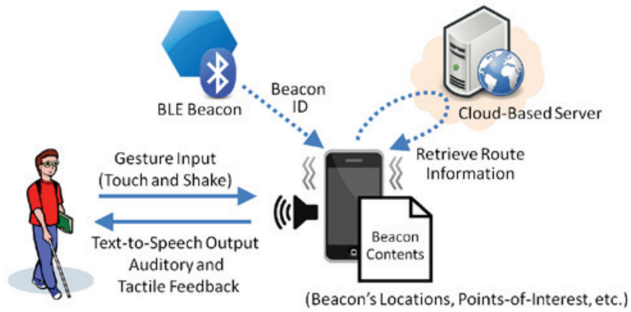

Figure 1: StaNavi system architecture

destinations. This test allowed us to identify and fix potential usability problems before conducting a user study. Through the design process described above, we have extracted the following user requirements that can realize independent navigation for blind travelers in a large train station:

- One-handed operation should be allowed because the other hand is often occupied with holding a cane or guide dog.
- Destination input should be performed with confidence and certainty. Speech input may not work well in noisy places, and text input may be hard to perform for users unfamiliar with smartphone use.
- Information on the current location and direction faced should be accessed directly and easily anywhere on the app.
- Overall understanding of the space should be supported.
- Route descriptions should be as detailed as possible, particularly for convoluted paths or open spaces.
- Warnings of poor signals and deviations from a route should be provided; in case of signal loss, the last position should be repeated.

3.2 System Overview

As illustrated in Figure 1, the StaNavi system architecture consists of a user smartphone, BLE infrastructure, and a cloud-based server that calculates the route from origin to destination. The BLE infrastructure allows users to determine their approximate locations in close proximity to points of reference (POR) in a station (e.g., platforms, exits, toilets, elevators). When a smartphone detects a BLE beacon's signal, StaNavi receives the beacon's unique ID, which can be used as a key to access relevant information (a location name, nearby POI, directions to adjacent beacons, etc.) from contents stored by the app. StaNavi takes

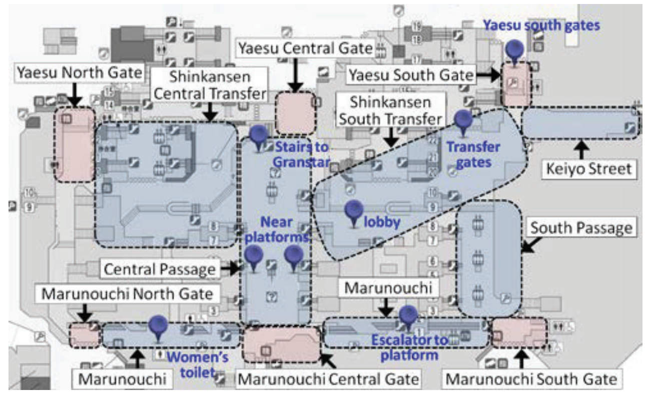

Figure 2: Areas defined and some points-of-reference

advantage of BLE beacons installed on signs and the ceiling that have been experimentally deployed by East Japan Railway. StaNavi runs on a BLE-enabled smartphone. The user interacts with StaNavi using gestural inputs and Text-to-Speech (TTS) output with auditory and tactile feedback. Based on user requirements described in the previous subsection, the current version of StaNavi includes three main functionalities.

"Where am I": Users can obtain direct access to their current location and four directions that are faced – the Marunouchi side, Yaesu side (both are famous districts in Tokyo), South, and North.

"Free Roam": Users can obtain automatic notification of their current location when they are within range of PORs. The user also can get detailed information if available. This functionality allows users to explore and learn about the surrounding facilities of the train station.

Navigation: Users can obtain turn-by-turn directions from their current location to a desired destination. To guide the user to a destination, StaNavi introduces PORs (beacons) on the route in order. Every time the user's presence is detected in the vicinity of a POR, StaNavi provides instructions on how to get from the current POR to the next POR. The user also can obtain navigation cues if they are available.

3.3 Information Provided for Easy Navigation

Recognizing the importance of meeting information needs for independent traveling in a large and complex environment, StaNavi provides rich information that helps VI understand a space and navigate to and from places with ease. Table 1 shows an overview of the information provided by StaNavi.

Table 1: Overview of the information provided by StaNavi

Functionality	Information Type		Example message
Free Roam	Current location		"You are near the Tokaido line platform in the Central Passage area. Detailed information exists. " "The passage width is approximately 17 m. 34 staircase steps to the platform."
	Detailed information about surroundings		
Navigation	Route instruction	Current location	"You are near the Shinkansen South Transfer Gate in the Central Passage area. Turn right near the 7th platform and go 25 m to the south. 50 m left to the destination. Navigation cue exits." "Access to the Shinkansen South Transfer area is between the 7th and the 9th platform."
		Direction to next POR	
		Distance to next POR	
		Distance left to destination	
		Navigation cue	
	Route overview		See Figure 4.
	Warning of poor signals and deviations		"You may be off the route. You can reroute from the Navi Main menu."

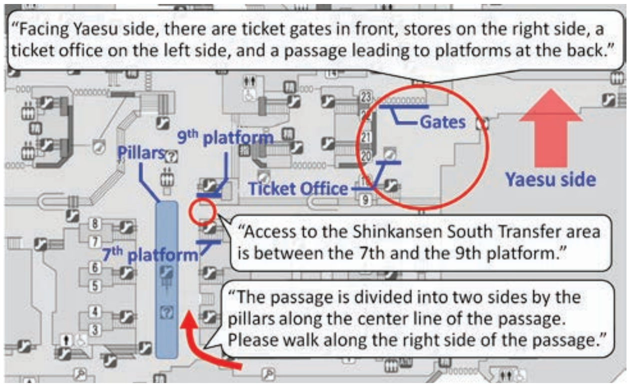

Figure 3: Examples of navigation cues provided by StaNavi

3.3.1 Current location
Spatial representation of a large environment is generally organized into a hierarchical structure in human memory [13] (e.g., the location of a desk in a room on the first floor of a building). To let VI intuitively and easily determine where they are in such a large station, StaNavi presents their current location in two levels of a hierarchy (e.g., "at the women's toilet in the Marunouchi area"):

- *Area*: Meaningful chunks of a train station, such as passages, lobbies, and around gates. Figure 2 shows the areas defined in StaNavi.
- *Point-of-Reference*: Specific locations that can be important reference points when navigating the station and can be identified by beacons (platforms, gates, escalators, elevators, staircases, intersections, the entrances of facilities, such as toilets and stores, etc.). A total of 55 PORs were used in StaNavi (Figure 2 shows some PORs).

3.3.2 Detailed Information
In "Free Roam" mode, StaNavi offers detailed information about surroundings that can raise VI's spatial awareness. This information includes the width of the passage, the number of staircase steps to the platforms, the presence of facilities, such as elevators and escalators in the passages, two relative directions (left and right) when standing against the staircase to the platforms, and the floor level difference in the lobby.

3.3.3 Navigation Cues
A default instruction message (Table 1) notifies the user when detecting a POR on the route. Regarding the description of direction changes, we used four absolute directions (Marunouchi side, Yaesu side, South, and North). For the diagonal directions, we used a clock-positioning system (e.g., "facing south, change direction to 2 o'clock"). In addition to the default instruction, StaNavi offers navigation cues to help VI orient themselves in convoluted paths and open spaces. This information mainly includes the exact position of a byway, the description of a path that goes through wide passages, and the description of spatial relations to surroundings in a large space (Figure 3).

3.3.4 Overview of the route
The importance of route preview information has been recognized for helping VI establish an overall cognitive map of an area [14]. In our design process, we have also identified that gaining a route overview in advance may enhance user confidence in the navigation process. StaNavi provides a route overview in a way that divides the total route into area-level steps, as shown in Figure 4. Audio information on the route overview begins with the total distance and the number of areal-level steps to a destination, and is then followed by area-level steps in order.

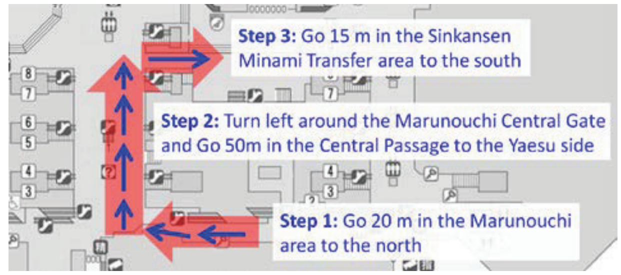

Figure 4: An example of route overview information. Red arrows indicate area-level steps that summarize the total route, and blue arrows show turn-by-turn directions

3.3.5 Warnings of poor signals and deviations
If the user is outside of all beacon regions, StaNavi provides a warning and reads aloud the last known position. For example, "currently, you are outside of the beacon region. Your last known location is the women's toilet in the Marunouchi area." If the user deviates from the route (detecting a beacon that is not included on the route), StaNavi provides a message shown in Table 1.

3.4 User Interface
To enable users to control StaNavi with one hand, we used a set of simple touch gestures – one-finger swipe up and down, two-finger swipe left, one- and two-finger tap, double-tap, and long press – and a shake gesture, as shown in Figure 5. Users can perform the touch gestures anywhere on the screen without being restricted by a fixed layout so that it allows one-handed thumb use of StaNavi (note that the command assigned to the two-finger swipe left gesture can be substituted by a shake gesture).

We took advantage of interfaces that have been designed for our previous smartphone-based system [11] and have been shown to be useful for VI in navigating the app's information hierarchy. When starting StaNavi, users can choose one of the two modes according to their usage scenarios: "Free Roam" mode to explore the station and "Navigation" mode to reach their destinations (Figure 5A). In "Free Roam", StaNavi automatically reads aloud the current location with both auditory and tactile feedback when detecting a beacon (Figure 5B). Users can obtain detailed information by swiping down. In "Navigation", users can input a desired destination by selecting one of three categories (Figure 5C), then a specific location (Figure 5D). This hierarchical selection allows users to easily input their destinations with confidence and certainty. After selecting a destination, StaNavi transitions to the Navi Main screen (Figure 5E) and sends a request to the server for route information. When the download is finished, users will receive a voice notification that says, "The route information has been downloaded." In the "Navi Main" menu, users can select one of four items: Preview, Navi Start, Reroute, and Navi Quit (Figure 5E). In "Preview", users can access the route overview information, described in Section 3.3.4, by performing swipe up and down gestures that read aloud each area-level step (Figure 5F). Selecting "Reroute" will re-request

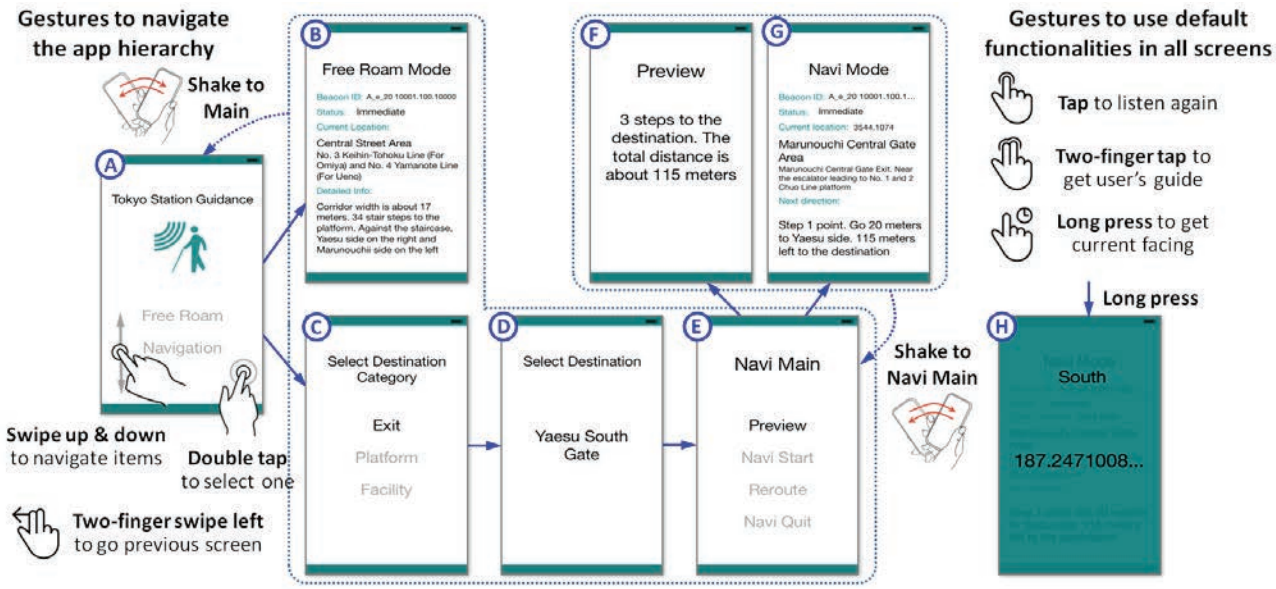

Figure 5: Screen transition flow and performed gestures of StaNavi

route information from the current location to the selected destination without a screen transition. When the download is finished, a voice notification will be produced. Users can go back to the top screen by selecting “Navi Quit”. Selecting “Navi Start” transitions to the “Navi Mode” screen (Figure 5G). In “Navi Mode”, StaNavi reads aloud turn-by-turn instructions with both auditory and tactile feedback whenever it detects a beacon. Users can access navigation cues by swiping down.

To allow users to determine the direction they are facing, we adopted a pointing-based interaction that enables users to retrieve relevant information on a desired direction by pointing smartphones in that direction. This method has been identified as a useful interaction technique for letting VI indicate their areas of interest [12] and has been adopted by commercial apps, such as BlindSquare. In all screens, tapping and holding (long press) with one finger brings up the screen (Figure 5H), which reads aloud four absolute directions of Tokyo Station according to the direction that the smartphone is pointing toward. Users also can access their current location in most screens (Figure 5C, D, E, and F) by one-finger tap; in “Free Roam” and “Navi Mode”, a one-finger tap repeats the last description. A two-finger tap anywhere in the app provides guidance on the use of each screen. For example, “Destination category selection screen. Swipe up and down to navigate categories and double-tap to select.” Additionally, users can go back to the top screen or “Navi Main” directly by shaking their smartphones, which can be helpful for not only one-handed operation, but also for escaping from an unexpected situation and starting over, like pressing a reset button.

3.5 Implementation

StaNavi is implemented on iOS 8 platform and currently runs on BLE-enabled Apple iPhone 5S and 6. StaNavi makes use of the device’s built-in accelerometer and gyroscope sensors to detect shake-motion events. We also used AVSpeechSynthesizer API included in iOS7 and higher platforms to offer TTS.

In the early development stage, after testing the prototype several times in the field, we found that proximity estimations were unstable and fluctuated greatly in some areas where beacons were installed densely, which could cause VI to feel anxious and confused. Therefore, to improve beacon detection stability, we empirically adjusted which beacons are used for StaNavi. In particular, we grouped adjacent beacons to represent the same POR and ignored some beacon signals.

The overall navigation process of StaNavi is shown in Figure 6. When a user selects a destination, StaNavi communicates with the server via HTTP. The server calculates the shortest path using Dijkstra’s algorithm and returns relevant information in XML format. StaNavi then parses it and makes route instructions for reaching the destination. Our system scans for beacons every 2 seconds, updates the current location, and provides proper instructions until the user detects the last beacon on the route. If StaNavi detects a beacon not on the route, it waits for 30 seconds before sending an off-route message in order to ensure user deviation.

4. EVALUATION

Experimental evaluation of StaNavi was conducted in the field to verify (1) the effectiveness of enabling people with visual impairments to independently navigate a complex train station and (2) the usefulness of features for supporting easy navigation. StaNavi was tested on the first floor of Tokyo Station where a total of 100 beacons were deployed. The experiment was

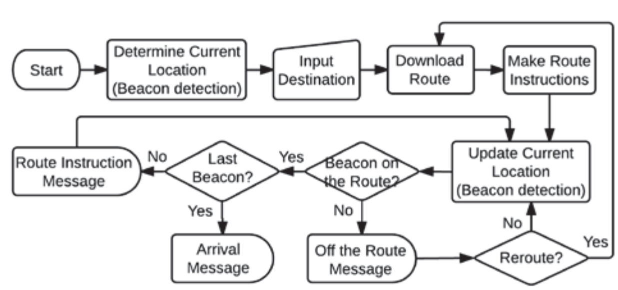

Figure 6: Flowchart of StaNavi’s navigation process

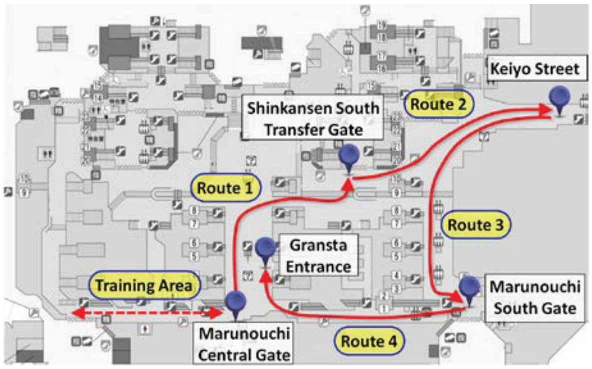

Figure 7: Maps showing given destinations and the routes that participants took. The total distance is about 600 meters

conducted over four days, and eight visually impaired people participated in total. User interactions with StaNavi – detected beacon identifiers, use of functionalities, such as direction determination and rerouting, and screen transitions – were recorded with timestamps in a text (.txt) log file.

4.1 Participants

We recruited eight visually impaired participants (three males and five females; P1-P8) with an average age of 24.4 (SD=7.3). All of them were totally blind except one who had low vision. Six participants were current iOS users. Seven participants go out and use public transit every day, and all of them use a white cane. Additionally, we asked about the frequency of Tokyo Station use; four participants use it at least once a year; two participants use it at least once a month; one participant uses it at least once a week; and one participant rarely uses this station. The entire study took approximately 2 hours. The whole process of the experiment was conducted in Japanese and was videotaped for later analysis.

4.2 Procedure

Considering key locations inside Tokyo Station, we asked participants to perform the following four navigation tasks (Figure 7): (1) Route 1: From Marunouchi Central Gate to Shinkansen South Transfer Gate, (2) Route 2: From Shinkansen South Transfer Gate to Keiyo Street, (3) Route 3: From Keiyo Street to Marunouchi South Gate, and (4) Route 4: From Marunouchi South Gate to Gransta Entrance.

To help users develop a clear impression of the usefulness of the route overview information, we asked participants to use the preview functionality before performing the first two tasks or last two tasks. Half of the users followed Routes 1 and 2 with route previews and followed Routes 3 and 4 without route previews; the other half did the opposite. At the beginning of the tasks, we provided all participants with training and practice until they felt familiar with StaNavi in the training area shown in Figure 7. For

Figure 8: A neck strap and speaker used in the experiment

Figure 9: Users interacting with StaNavi: (A) Determining directions by pointing the device, and (B) listening to route instructions while walking

the users' convenience, we provided a neck strap for smartphones. A portable speaker was also offered, which directly plugged into the earphone jack of the smartphone to amplify sound, because Tokyo Station is often very noisy (Figure 8).

For each task, users were led to the start location where the experimenter would check the detection of the first beacon on the route and hand the device to users. Each task began when the participant selected "Navi Start", and ended when the participant said he or she had reached the given destination. We especially asked the participants to navigate to the given destinations as independently as possible utilizing the reroute functionality if needed. Two or three experimenters monitored the participants' safety at all times, but provided assistance only in dangerous situations. The experimenter intervened in the case of a user's request for help; outside of the experiment area (e.g., when entering stores, platforms); and outside of the range of the beacon's signal. In those cases, the experimenter led the users to the next POR location on the route so that they could continue the task. After finishing all tasks, participants were asked to answer a questionnaire to collect qualitative experiences. Figure 9 shows participants navigating the station using StaNavi.

4.3 Results

To evaluate the effectiveness of enabling independent navigation, we analyzed data on task completion rate, task completion time, deviation, and help-seeking situations, as shown in Table 2. For evaluating the usefulness of features provided by StaNavi, we conducted a questionnaire survey.

4.3.1 Task completion rate and time

We considered the task a success when the users detected the last beacon on the route, which means that they were able to navigate within 2 meters of the target location. Each participant performed four tasks, amounting to a total of 32 trials. They completed all trials without failure, taking alternative paths (rerouting) appropriately. The average task completion time is shown in Table 2. Considering the time taken to reroute, which particularly occurred more than one time per trial in Routes 1 and 2, the time taken for navigating to the given destinations would be acceptable.

4.3.2 The number of deviations

The number of times that rerouting occurred – the participants regarded themselves as off the route and tried to take an alternative route – was counted as the number of the user's deviations. Particularly, participants often deviated from Routes 1 and 2 (Table 2), which include some challenging points where people with visual impairments may have difficulty orienting themselves. A total of 38 deviations occurred during 32 trials,

Table 2: Data collected for each route

Task	Route 1	Route 2	Route 3	Route 4
Success rate	1.00	1.00	1.00	1.00
Avg. time (s)	550	466	403	301
Route length (m)	153	114	171	138
Time stdev	285	145	79	58
# of deviations	17	10	5	6
Avg. # deviations	2.1	1.3	0.6	0.8
# of interventions	4	5	1	4

requiring an average 1.2 times of rerouting per trial. However, this would be acceptable considering the use of StaNavi under realistic conditions, such as magnetic inference on the compass readings and fluctuations of proximity readings.

4.3.3 The number of interventions

During the whole experiment, a total of 14 interventions were provided (Table 2) for the following reasons: Nine times to secure participants' safety when they entered stores and platforms; four times to resume tasks when they were outside of beacon range; and one time to help a user who accidently launched another app. Note that there were no explicit requests for help from the participants. Furthermore, the critical situation of users going out of all beacon regions and not being able to return to the navigation process occurred only four times, indicating participants could generally reach their destinations independently.

4.3.4 Subjective Ratings

After finishing all tasks, we asked participants to complete a brief questionnaire to investigate the effectiveness of our system. Participants rated five statements using a five-point Likert scale (1=Disagree strongly, 5=Agree strongly). The list of statements, mean values, and standard deviations are shown in Table 3. The results confirm that StaNavi was generally well accepted by the participants. In particular, all participants found our system very useful and would strongly like to use it on smartphone, indicating StaNavi has great potential for large-scale adoption, given that six out of eight participants were smartphone users. We also asked participants to rate each functionality in terms of usefulness and ease-of-use using the same five-point Likert scale. Overall, participants found the given functionalities very useful (Table 4). On the other hand, perceived ease-of-use was somewhat varied by functionality, although generally higher. In particular, some users had difficulty using the direction determination functionality because they were required to keep pressing the screen while pointing the device in desired directions.

4.3.5 User Feedback

Overall, a number of participants liked our system. P6 said *"I appreciate that I could reach my destination just as I wanted, without anxiety."* P5 stated, *"It would be helpful to understand a train station I have never been."* Some participants commented positively about features provided by StaNavi. Three users were particularly fond of the route overview information. P5 said, *"It was useful in that I could predict the route in advance. This made me feel comfortable even if I might forget it during navigation."* P2 stated, *"Current location was easy to understand because of its hierarchical representation."* P3 commented that the navigation cues were helpful.

Table 3: Questionnaire results on overall system effectiveness

Statement	Average rating
Useful	4.88 (0.35)
Easy to use	4.00 (0.93)
Easy to learn	4.38 (0.92)
Felt in control	4.25 (0.71)
Would use on smartphone	4.75 (0.46)

Table 4: The ratings on Usefulness and Ease-of-Use for each functionality (Mean, SD)

Functionality	Usefulness	Ease-of-Use
Free roam	4.88 (0.35)	4.63 (0.52)
Navigation	4.75 (0.46)	4.00 (0.76)
Destination selection	4.88 (0.35)	4.88 (0.35)
Current location check	4.88 (0.35)	4.75 (0.46)
Direction determination	4.88 (0.35)	3.13 (1.25)
Preview	4.50 (0.93)	4.88 (0.35)
Reroute	4.75 (0.46)	4.25 (1.04)

Meanwhile, five participants found the clock-positioning system for heading in diagonal directions difficult to understand. Two participants suggested that although it increases the number of turns they should make, it would be better to use only three types of navigational instructions: Turn left, turn right, and go forward. Additionally, some participants provided recommendations to refine the interface for determining directions. For example, P3 commented on the need for a user's guide for using the direction determination functionality, such as "Rotate the device until the compass reading stabilizes." In addition, several participants mentioned the need for additional information on surrounding shops and facilities. Moreover, three participants suggested that route guidance based on tactile paving would be helpful.

5. DISCUSSION

It was encouraging that all participants achieved independent navigation to given destinations successfully. They actively used navigation cues and rerouted themselves by appropriately considering the concept of proximity sensing – it only let them know they were within close range of a specific location, rather than a precise position – and unstable sensor readings that might have sometimes provided incorrect information on their current location or direction faced. We observed a number of deviations of users in Routes 1 and 2. The beacon installed at the turning point of Route 1, the byway located between two platforms, was often detected after users passed that point because it was difficult to pinpoint such a byway with a relatively narrow width in a timely manner, although BLE technology generally provided sufficient accuracy in localization. Route 2, where users were instructed to proceed in a diagonal direction, was tricky to navigate for most participants. One participant stressed the need for continuous tactile or auditory feedback to orient herself and keep walking in the right direction in the case of moving diagonally. Further extension of StaNavi could integrate other positioning methods, such as DR, to improve position accuracy to reduce the incidence of deviation.

When users received the off-route message, they tended to become close to a corner, wall, or pillar to interact with StaNavi and avoid other passengers; however, those spots sometimes receive no signal, which caused users to disappear from all beacon regions. This issue will be partially addressed by putting beacons in those spots or providing an additional instruction to move away from those spots. We also observed that users effectively used navigation cues to orient themselves. In particular, all participants took advantage of information on spatial relationships in surroundings in the open space of Route 2. We believe that the key to navigation tasks for blind travelers in a large and complex space is effective support for their understanding of situations – poor signals, spatial relations to surrounding objects, environmental patterns (e.g., tactile paving), etc. Additional environmental cues, such as auditory (e.g., a beeping sound from a card reader at the entrance) and olfactory (e.g., the coffee aroma from a café) information can be helpful for identifying their location. Our next prototype will include environmental cues to allow blind travelers to gain a better understanding of surroundings so that more independent and confident navigation can be achieved.

6. CONCLUSION

In this paper, we have proposed an indoor navigation system, StaNavi – a smartphone-based navigation system for blind travelers in a large train station utilizing BLE technology. We iteratively co-designed StaNavi with blind users to provide features for ensuring easy and effective navigation. Unlike existing systems, StaNavi can be used from off-the-shelf smartphones without requiring additional hardware. Our user study conducted under realistic conditions demonstrated that our interaction design for one-handed operation and information on navigation cues and route overviews could encourage independence and confidence when navigating large and complex indoor environments. The user study presented "real-world" evidence of the effectiveness of using smartphones and BLE technology for facilitating independent navigation for people with visual impairments.

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8. REFERENCES

[1] Alghamdi, S., Van Schyndel, R., and Alahmadi, A. Indoor navigational aid using active RFID and QR-code for sighted and blind people. In *Proc. ISSNIP 2013*, IEEE, 18–22.

[2] Alkhanifer, A. A., and Ludi, S. Visually impaired orientation techniques in unfamiliar indoor environments: a user study. In *Proc. ASSETS 2014*, ACM, 283–284.

[3] Fallah, N., Apostolopoulos, I., Bekris, K., and Folmer, E. The user as a sensor: navigating users with visual impairments in indoor spaces using tactile landmarks. In *Proc. CHI 2012*, ACM, 425–432.

[4] Faria, J., Lopes, S., Fernandes, H., Martins, P., and Barroso, J. Electronic white cane for blind people navigation assistance. In *Proc. WAC 2010*, IEEE, 1–7.

[5] Fiannaca, A., Apostolopoulous, I., and Folmer, E. Headlock: A wearable navigation aid that helps blind cane users traverse large open spaces. In *Proc. ASSETS 2014*, ACM, 19–26.

[6] Flores, J. Z., and Farcy, R. (2014). Indoor navigation system for the visually impaired using one inertial measurement unit (IMU) and barometer to guide in the subway stations and commercial centers. In *Computers Helping People with Special Needs*, Springer, 411–418.

[7] Gallagher, T., Wise, E., Yam, H. C., Li, B., Ramsey-Stewart, E., Dempster, A. G., and Rizos, C. (2014). Indoor navigation for people who are blind or vision impaired: where are we and where are we going?. *Journal of Location Based Services*, *8*(1), 54–73.

[8] Guerrero, L. A., Vasquez, F., and Ochoa, S. F. (2012). An indoor navigation system for the visually impaired. *Sensors*, *12*(6), 8236–8258.

[9] Jain, D. Path-guided indoor navigation for the visually impaired using minimal building retrofitting. In *Proc. ASSETS 2014*, ACM, 225–232.

[10] Joseph, S. L., Zhang, X., Dryanovski, I., Xiao, J., Yi, C., and Tian, Y. Semantic indoor navigation with a blind-user oriented augmented reality. In *Proc. SMC 2013*, IEEE, 3585–3591.

[11] Kim, J. E., Bessho, M., Koshizuka, N., and Sakamura, K. Enhancing public transit accessibility for the visually impaired using IoT and open data infrastructures. In *Proc. Urb-IoT 2014*, ICST, 80–86.

[12] Kim, J. E., Bessho, M., Koshizuka, N., and Sakamura, K. (2014). SaSYS: A Swipe Gesture-Based System for Exploring Urban Environments for the Visually Impaired. In *Mobile Computing, Applications, and Services*, Springer, 54–71.

[13] McNamara, T. P. (1986). Mental representations of spatial relations. *Cognitive psychology*, *18*(1), 87–121.

[14] Ross, D. A., and Kelly, G. W. (2009). Filling the gaps for indoor wayfinding. *Journal of Visual Impairment and Blindness*, *103*, 229–234.

[15] Panëels, S. A., Olmos, A., Blum, J. R., and Cooperstock, J. R. Listen to it yourself!: evaluating usability of what's around me? for the blind. In *Proc. CHI 2013*, ACM, 2107–2116.

[16] Spindler, M., Weber, M., Prescher, D., Miao, M., Weber, G., and Ioannidis, G. (2012). Translating Floor Plans into Directions, In *Computers Helping People with Special Needs*, Springer, 59–66.

[17] Strumillo, P. Electronic interfaces aiding the visually impaired in environmental access, mobility and navigation. In *Proc. HSI 2010*, IEEE, 17–24.

[18] Tsirmpas, C., Rompas, A., Fokou, O., and Koutsouris, D. (2015). An indoor navigation system for visually impaired and elderly people based on Radio Frequency Identification (RFID). *Information Sciences*, *320*, 288–305.

[19] Zhang, D., Lee, D. J., and Taylor, B. (2014). Seeing Eye Phone: a smart phone-based indoor localization and guidance system for the visually impaired. *Machine Vision and Applications*, *25*(3), 811–822.

[20] Zhao, X., Xiao, Z., Markham, A., Trigoni, N., and Ren, Y. Does BTLE measure up against WiFi? A comparison of indoor location performance. In *Proc. European Wireless 2014; 20th European Wireless Conference*, VDE, 1–6.