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PERCEPT-V: Integrated Indoor Navigation System for the Visually Impaired using Vision-Based Localization and Waypoint-Based Instructions

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Abstract

In this paper, we introduce PERCEPT-V, an indoor navigation system for visually impaired users that uses vision-based localization and provides real-time navigation instructions to the chosen destination including the landmarks along the path. PERCEPT-V requires no sensor deployment in the physical environment. Based on tests in three different indoor environments, the offline digital map generation process of a new environment takes less than 1 minute per 3 square meters of the environment. The system was successfully tested with 9 blind and visually impaired users. The results show that all participants are satisfied with the system and they all completed all navigation tasks using PERCEPT-V.

Keywords

Indoor navigation, blind and visually impaired, vision based localization, navigation instructions

Introduction

According to the World Health Organization 2018, globally, it is estimated that approximately 1.3 billion people live with some form of distance or near vision impairment. In a study of behavior and challenges in indoor navigation tasks in an unfamiliar environment for blind people (Jeamwatthanachai, Wald and Wills), most of the participants agreed that navigating in unfamiliar public venues, e.g. university, hospital, supermarket, museum, etc., is a very challenging task. Most of them have to rely on a sighted guide.

Using GNSS (Global Navigation Satellite System) for outdoor localization, navigation applications such as Google Maps facilitate wayfinding tasks for both vehicle and pedestrian use. However, due to attenuation and scattering of GNSS signals in indoor environments, outdoor navigation applications cannot be used in indoor environments. In spite of the fact that there are several promising solutions for indoor navigation (Abu Doush, Alshatnawi and Al-Tamimi) (Ahmetovic, Gleason and Ruan) (Sato, Oh and Naito) (Cheraghi, Namboodiri and Walker) (Ganz, Schafer and Gandhi) (Ganz, Schafer and Tao) (Kim, Bessho and Kobayashi) (Giudice, Whalen and Riehle) which were successfully tested with human subjects, none of them were widely adopted in indoor venues.

BVI indoor navigation systems can be characterized by the following criteria:

1. **Localization technology** - the type of technology used to localize the user in the physical environment includes: Wi-Fi (He and Chan), NFC (Near Field Communication) sensors (Sakpere, Mlitwa and Oshin), BLE (Bluetooth low energy) sensors (Zuo, Liu and Zhang), inertial sensing (dead reckoning) (Kang and Han), magnetic sensing (Montoliu, Torres-Sospedra and Belmonte), infrared and LED light (Zhuang, Hua and Qi), and computer vision (Piasco, Sidibe and Demonceaux).

2. **Sensor deployment and maintenance efforts –** sensor deployment effort correlates with the localization technology. For example, BLE-based localization requires the installation of BLE sensors throughout the physical space. In addition to the deployment effort, the sensor infrastructure requires maintenance such as tags' replacement due to vandalism, malfunction and/or battery depletion. Therefore, sensor-based infrastructure leads to an increased cost to the venue owners. On the other hand, vision-based and inertial localization does not require any deployment of sensors in the environment lowering the deployment cost. Both sensor and vision-based approaches require "digital maintenance" (change in the digital representation of the physical environment) in case the physical environment undergoes renovations (similarly, outdoor GIS systems need to be updated when roads are added/removed, or traffic regulations are changed).
3. **User device** - Most systems leverage the sensors, display, computation, and communication modules embedded in the Smartphone. Some systems require specialized devices to facilitate localization and navigation tasks. Use of specialized devices increases the cost to the user and may hinder the adoption of this technology.
4. **Navigation instructions –** the navigation instructions guide the user's journey to the chosen destination through the physical environment.
    a. **Classification 1**: We classify the instructions in three groups based on the time the instructions are generated and when they are delivered to the user:
        i. **Off-line instructions** - generated during the system deployment phase or just before the user's trip. These instructions are stationary and only

available between POIs assuming the users know their location. No real-time localization is required.

ii. **User-solicited instructions** - generated during the preparation process or before the trip. The instructions are updated following the users' location and presented to the users when they prompt the system. Real-time localization is required.

iii. **Continuous instructions** - dynamically generated based on the user's current location (similar to outdoor navigation apps as Google maps). Real-time localization is required.

b. **Classification 2**: We can further classify the instructions based on their contents:

i. **Shoreline**: Instructions describe trailing movements, which is commonly used as an orientation and mobility skill for BVI travelers. An example is "follow the wall on your right and turn right at the next opening." (Ganz, Schafer and Gandhi),

ii. **Turn-by-turn**: Instructions include a set of turns such as turning direction, the distance to turn, and contextual information at the turn. For example: "please turn right into an intersecting hallway about 20 steps ahead." (Sato, Oh and Naito)

iii. **Additional information**: Some systems also provide additional information about the environment surrounding the user during the journey such as points of interest or description of specific areas.

c. **User trials** – whether the system was tested with human subjects and how many subjects participated. We emphasize that testing with blindfolded subjects cannot reflect the sentiment of BVI users. This is due to the fact that BVI users have undergone orientation and mobility training as well as possess very strong hearing sense not usually found in sighted people.

d. **Environment structure and complexity** – whether the system was designed and/or tested in specific environments. The navigation strategy in corridor-based environments and in open areas is quite different for BVI travelers.

We first introduce PERCEPT-V and then provide a comparison with other indoor navigation approaches for BVI users.

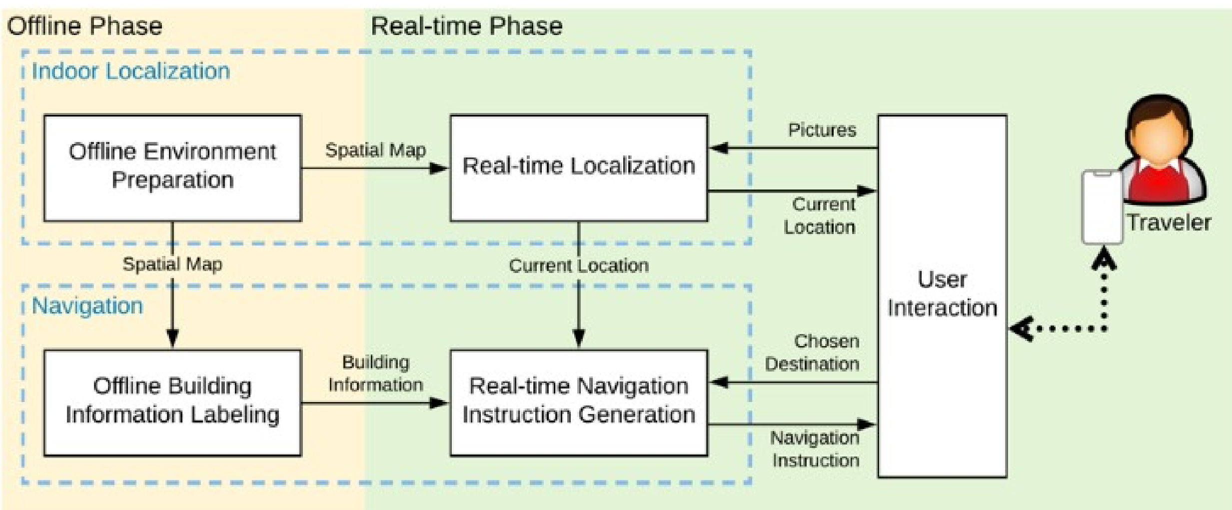

Fig. 1. Overview of System Architecture.

PERCEPT-V system architecture is introduced in Fig. 1. It includes offline and real-time phases. In the off-line phase, we include the environment preparation for both the localization and navigation modules. In the real-time phase, we continuously determine the user location and provide the corresponding navigation instructions. PERCEPT-V meets the following criteria introduced above:

1. **Localization technology -** Vision-based indoor localization approach that continuously determines the user's location in the environment.
2. **Sensor deployment and maintenance efforts –** PERCEPT-V does not require sensor deployment in the physical environment. It requires the generation of the digital map of the environment and its "digital maintenance" in case the physical environment undergoes renovations.
3. **User device –** the user device is a smartphone. We developed a vision free iOS application which includes the user interaction as well as the localization and navigation modules.
4. **Navigation instructions –** Navigation guidance includes continuous turn-by-turn instructions, region related instructions, and pass-by point-of-interest information.
5. **User trials –** we tested PERCEPT-V with 9 BVI users.
6. **Environment structure and complexity –** system tested in corridor-based and large open spaces.

Table 1 compares several recent indoor navigation systems for BVI users using the criteria introduced above. We only include papers that provide **real-time** instructions to the destination from the user current location as determined by the system (like Google Maps). We note that rows 1-6 in Table 1 display systems using sensor-based localization that require sensor deployment and maintenance in the environment. As mentioned above, sensor infrastructure increases the system cost which includes sensor deployment as well as maintenance. MagNav (Giudice, Whalen and Riehle) and the proposed system, PERCEPT-V do not require sensor deployment. MagNav is applicable to environments with steel structures and assumes travelers stay close to the wall (i.e. shorelining), which is not applicable to environments with large openings. In contrast, PERCEPT-V provides continuous turn-by-turn navigation instructions, and is applicable to any indoor environment.

Table 1. Comparison Table of Surveyed Systems and the PERCEPT-V.

Project	**Localization**	**Sensor deployment in building**	**User device**	**Instructions**	**Human trials**	**Building structure**
ISAB	Wi-Fi, Bluetooth, RFID	Wi-Fi AP, Bluetooth & RFID tags	Smartphone + RFID reader	Continuous Turn-by-turn	20 BVI	Specific building (libraries)
NavCog, NavCog3	BLE finger-printing	BLE tags	Smartphone	Continuous Turn-by-turn with POIs	6 BVI [12], 10 BVI [13]	Corridor-based + openings
Guide-Beacon	BLE proximity + compass	BLE tags	Smartphone	Offline Turn-by-turn	7 BVI	Corridor-based + openings
PERCEPT (2012)	NFC	NFC tags	Smartphone	Offline Shoreline with POIs and areas	24 BVI	Corridor-based
PERCEPT (2018)	BLE	BLE tags	Smartphone	User-solicited Shoreline with POIs and areas	6 BVI	Corridor-based + openings
StaNavi	BLE proximity + compass	BLE tags	Smartphone	User-solicited Turn-by-turn	8 BVI	Corridor-based + openings
MagNav	Inertial + Magnetic	No	Smartphone + body worn sensor	Continuous Shoreline	12 BVI	Building with steel structure
PERCEPT-V	Vision + inertial	No	Smartphone	Continuous Turn-by-turn with POIs and areas	10 BVI	Corridor-based + openings

The rest of the paper is organized as follows. Section 2 introduces the indoor localization process and Section 3 details the navigation instructions generation process. Section 4 introduces the testing environment along with a scenario. Section 5 discusses the trial results with BVI users and Section 6 concludes the paper.

Indoor Localization

PERCEPT-V which uses vision-based localization requires the following offline and real-time processes:

1) **Offline preparation of a new indoor environment**:
    a. **Data collection –** We take a set of videos that cover the indoor environment using the camera system shown in Fig. 2. The recording should follow highly utilized paths in the environment. This step takes no longer than the time to walk through these paths.
    b. **Spatial map generation –** A virtual representation of the environment is generated from the video footage using Structure-from-Motion pipeline, COLMAP (Schonberger and Frahm) (Schonberger, Zheng and Frahm) (Schonberger, Price and Sattler). It is used for real-time localization. Based on tests in three different environments ranging from 300 square meters to 2700 square meters, this process will take about 1 minute per 3 square meters of the coverage area using a 3.5 GHz 4 core desktop.
2) **Real-time localization using picture-based location estimation –** To determine the user location, we use the pictures taken by the user (the user is guided how to take the pictures as explained in Section 4) during the navigation process, the spatial map which was generated in the offline phase and the iOS built-in library, ARKit.

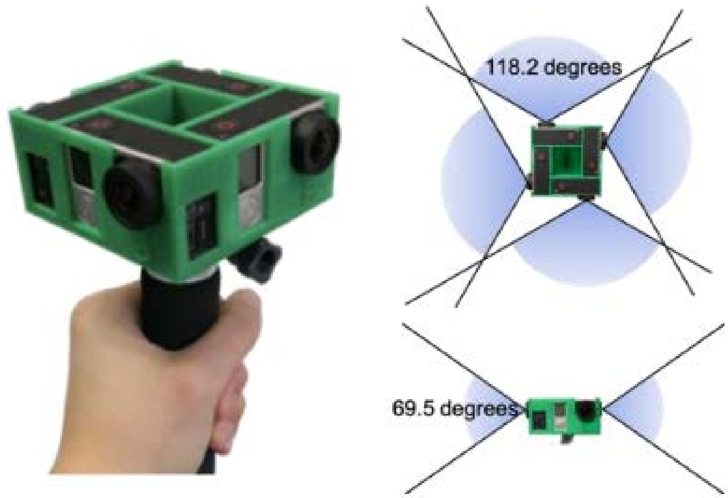

Fig. 2. Multiple Camera System used in Capturing Process.

Navigation

The navigation instructions provided in PERCEPT-V contains different types of information about the environment such as landmarks, waypoints, and regions. To provide this information we use a multi-layer graph-based data structure that organizes the landmarks, waypoints, and regions of the environment. Each landmark or waypoint is represented as a node. Any landmarks (or waypoints) that are in line-of-sight are interconnected by a link. Any position inside a region is in line-of-sight to any landmarks or waypoints in it. The optimal path from the user location to the chosen destination is determined by Dijkstra’s algorithm (Dijkstra) and includes a list of waypoints to the destination.

Two types of announcements are posted in addition to the navigation instructions:

1) **Region change**: For example: “you are in …” or “you are in the intersection area of … and …” Once the user’s location changes to another region, the following message informs the user: “you have left … and entered …” Without any region change, the current region will be repeatedly announced at a low frequency (once

per 12 seconds). This will help the user build a mental map of the indoor environment.

2) **Landmarks along the path**: Once a landmark is in a certain range of user's current location, a message in the form of "… is at your ... o'clock". This information can serve as an additional context to build a mental map.

An example of the instructions is provided in the next section.

Evaluation Site and Scenario

We selected the Campus Center at the University of Massachusetts Amherst as an evaluation site since it is a large and dynamic hub with vast open areas, it has considerable foot traffic as well as changing environment due to different events that take place in the space. The following scenario illustrates how PERCEPT-V system works in the Campus Center (see Fig. 3 for markers that represent landmarks).

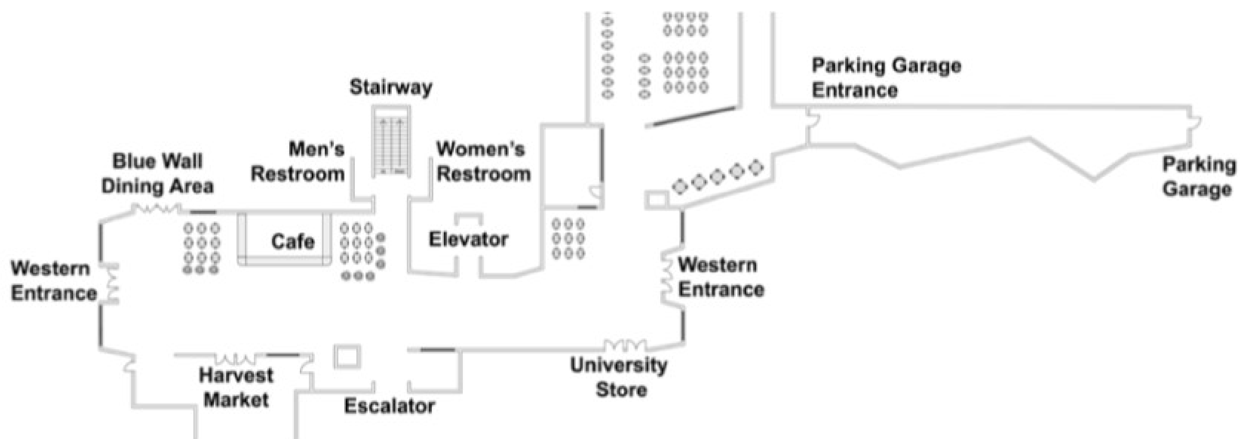

Fig. 3. Floorplan of navigation scenario in Campus Center (UMASS).

1) Arriving at Campus Center (Marker 1): Aaron enters the campus center through the parking garage. Aaron opens PERCEPT-V App. which states: "Use take picture button to determine location." Aaron selects the 'Take Picture' button from the home screen of the app. The app then assists Aaron in taking three pictures of the

environment through voice prompts and haptic feedback. After the localization is complete the app states: “Location determined. You are located on the main floor of the campus center. Select a destination from the list below.”

2) Navigating to Intersecting Hallway Waypoint (Marker 2): Aaron selects the café and PERCEPT-V app responds “Start navigation to café. Let’s head to the intersecting hallway at your 12 o’clock 78ft away.” Aaron begins walking towards the intersecting hallway and the app announces “12 o’clock 65 ft. away.” These orientation and distance announcements are continuously provided in real-time giving Aaron the ability to correct his course dynamically.
3) Navigating to Western Lobby Waypoint (Marker 3): Once Aaron reaches the intersecting hallway, PERCEPT-V app announces “Waypoint updated. Let’s head to the western lobby at your 9 o’clock, 58 ft. away. Then turn right when you reach there.” Aaron turns and starts walking towards the western lobby. At this time there happens to be a campus tour in which a large crowd of fifty people is moving through the western lobby. Aaron maneuvers through the crowd but ends up overshooting the waypoint and reaches the University Store. Since PERCEPT-V app continues to provide orientation and distance to Aaron “6 o’clock 32 feet away,” he seamlessly is able to correct his course and reaches the western lobby waypoint.
4) Navigating to Main Corridor Waypoint (Marker 4): Aaron arrives at the western lobby waypoint and PERCEPT-V app announces “Let’s head to the main corridor to your 9 o’clock 102 feet away. Then turn right when you reach there.” Aaron turns and starts walking towards the main corridor and maintains his trajectory using the

orientation and distance updates provided by the app. As Aaron is walking, he is informed by the app that the "Restrooms are to his 3 o'clock."

5) Navigating to Café Destination (Marker 5): As Aaron reaches the main corridor waypoint, PERCEPT-V app announces "Waypoint updated. Let's head to the destination Café at your 9 o'clock, 33 ft. away." Aaron turns toward the café, and once he is approximately 15 ft. away, the app informs him "The destination café is in your proximity approximately 15 ft. to your 11 o'clock. The café is composed of a long counter that is waist-high." Aaron identifies the counter and successfully reaches his destination and selects the 'Cancel Navigation' button to end the journey.

5. Human Subjects Trials

All aspects of the human-subject-trials (e.g. recruiting procedures, the trials, and the post-trial evaluation process) have been approved by the UMASS Institutional Review Board (IRB). In our study participants must be: 18 years of age or older, legally blind or visually impaired, and have no further mental or physical impairment. Participants were recruited through Certified Orientation and Mobility Specialists from the Massachusetts Commission from the Blind who have access to a directory of registered BVI for the state of Massachusetts. We had a total of 9 participants. A baseline survey was administered to each participant (results are shown in Table 2). The study procedures and trials results are discussed below.

Procedures: Each session with a BVI participant can take up to, but no more than three hours. Each session includes three parts: orientation, trial, and a qualitative questionnaire as detailed below:

Part I – Hands-On Orientation: This part includes: 1) *Sit-down orientation*: The participant is introduced to PERCEPT-V app by the experimenter, and 2) *On-site orientation*:

The participant uses PERCEPT-V app in the Campus Center to navigate to destinations that are not included in the actual trial.

Part II – PERCEPT-V Trial: The following navigation tasks are provided to the user one at a time (see Figures 4 and 5): **Task 1**: Western Entrance (0) to Harvest Market (1), **Task 2**: Harvest Market (1) to nearest Elevators (2), **Task 3**: Elevators (2) to Café (3), **Task 4**: Café (3) to Parking Garage (4), **Task 5**: Parking Garage (4) to nearest Escalators (5), **Task 6**: Escalators (5) to Room 172 (6) and **Task 7**: Room 172 (6) to nearest Stair (7). A navigation task is determined successful when the participant reaches the destination independently relying only on his/her mobility skills and PERCEPT-V app.

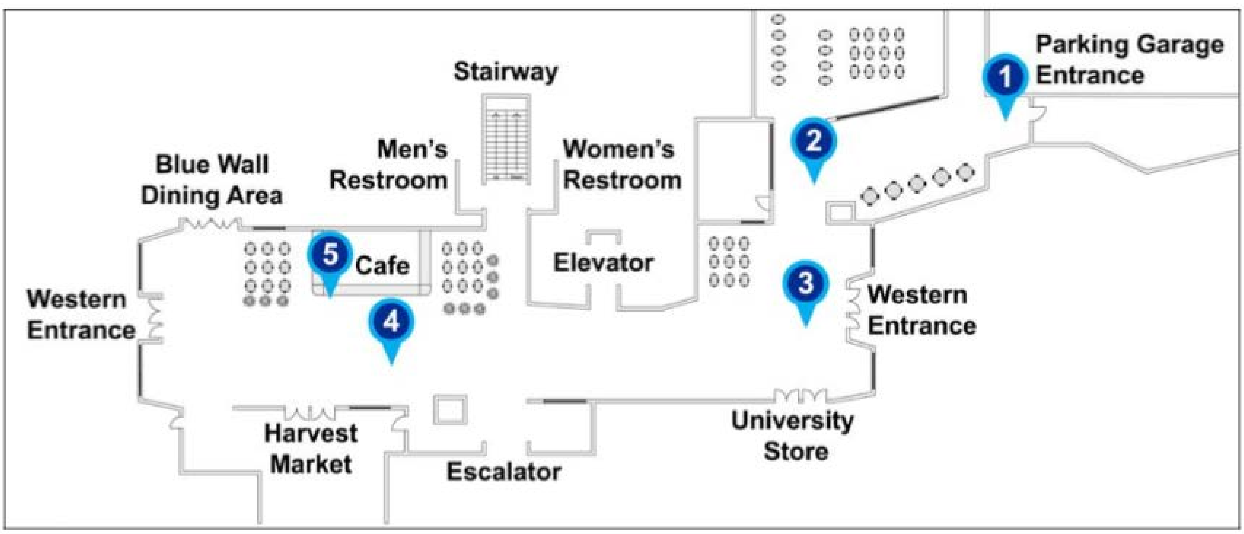

Fig. 4. Trial Destinations in Main Level of Campus Center.

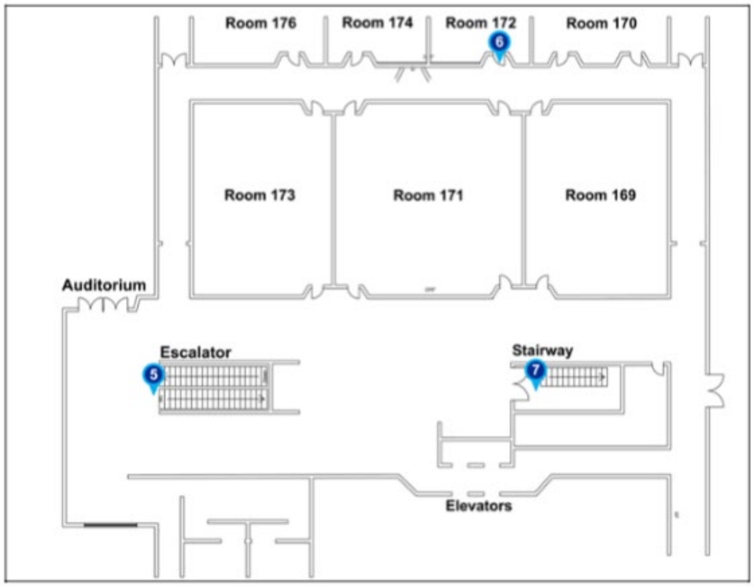

Fig. 5. Trial Destinations in Basement Level of Campus Center.

Part III – Post Trial Questionnaire

After completion of the trial we collect participant's feedback and experience using a qualitative questionnaire.

Table 2. Participants (P1-P9) Baseline Survey Answers.

Participants	**P1**	**P2**	**P3**	**P4**	**P5**	**P6**	**P7**	**P8**	**P9**
Age	44	38	25	34	44	58	54	26	65
Gender	Male	Male	Male	Female	Male	Male	Male	Female	Male
Race	African American	Latino	White	White	White	White	White	White	White
Vision (LP – light perception)	LP	LP	None	Partial	Partial	Partial	Partial	None	Partial
Field of View	-	-	-	Full	Full	Full	None	-	Full
Mobility Aid	White Cane	White Cane	Guide Dog	White Cane	None	White Cane	White Cane	White Cane	Telescope Magnifier
Technology improves My daily life	Strongly Agree	Strongly Agree	Strongly Agree	Agree	Neutral	Agree	Strongly Agree	Strongly Agree	Strongly Agree

Participants	P1	P2	P3	P4	P5	P6	P7	P8	P9
Using a smartphone is important to me	Strongly Agree	Agree	Strongly Agree	Agree	Strongly Agree	Strongly Agree	Disagree	Slightly Agree	Strongly Agree
I consider myself savvy with technology	Strongly Agree	Strongly Agree	Strongly Agree	Slightly Agree	Slightly Agree	Agree	Neutral	Strongly Agree	Agree
Independence in traveling is important to me	Strongly Agree	Strongly Agree	Strongly Agree	Strongly Agree	Strongly Agree	Agree	Strongly Agree	Strongly Agree	Strongly Agree

Observations

Table 3 includes observations per navigation task per user quantified as follows: 1 - reached destination, 2 - reached destination but needed assistance with UI (take a picture or select destination), and 3 - unable to reach the destination All participants were successful at completing all navigation tasks. Participants P4, P5, P7, and P8 needed assistance in interacting with the application in order to reach the destination. In all cases, this interaction was at the beginning of the journey for either taking the picture or selecting the destination. Note that all the participants that needed assistance were unfamiliar with how to use Voiceover on the iPhone. They were given a tutorial during the orientation, but it is important to note that these participants were simultaneously learning how to use PERCEPT-V app and Voiceover accessibility services. All participants familiar with Voiceover did not require any assistance. It’s important to note that none of the participants asked for assistance, because of the failure of localization. When participants took pictures but got an unsuccessful localization, they were informed by the application to retake another set of pictures in different angles and/or positions. This typically happened in the featureless areas.

Table 3. Per task and per participant observations. Participants P1-P9 and navigation task observation: 1-reached destination, 2-reached destination but needed assistance with UI (take picture or select destination), 3-unable to reach destination.

Tasks	**P1**	**P2**	**P3**	**P4**	**P5**	**P6**	**P7**	**P8**	**P9**
Task 1	1	1	1	2	2	1	2	1	1
Task 2	1	1	1	1	2	1	2	1	2
Task 3	1	1	1	1	1	1	1	1	1
Task 4	1	1	1	2	1	1	1	1	1
Task 5	1	1	1	1	1	1	1	1	1
Task 6	1	1	1	1	1	1	1	1	1
Task 7	1	1	1	1	1	1	1	1	1
Uses Voiceover	Yes	Yes	Yes	No	No	Yes	No	Yes	No

Table 4. Post-Trial Questionnaire Statements.

#ID	**Statement**
A	It is easy to learn how to use the PERCEPT-V system
B	It is easy to use the PERCEPT-V system
C	The PERCEPT-V trial design was easy to complete
D	The PERCEPT-V app user interface is clear
E	The PERCEPT-V system provided sufficient re-orientation information when lost
F	I am confident I can reach a destination using the PERCEPT-V system

Table 5. Post-Trial Questionnaire using Likert Scale Scores.

Statement ID#	**Avg.**	**P1**	**P2**	**P3**	**P4**	**P5**	**P6**	**P7**	**P8**
A	6.11	6	7	7	7	4	6	4	7
B	5.89	7	6	7	6	5	6	5	5
C	6.44	7	6	7	7	5	6	6	7
D	6.33	7	7	7	7	5	6	6	6
E	5.89	6	7	7	6	4	6	5	6
F	6.22	7	7	5	6	6	6	5	7
Avg. Per Participant	6.15	6.67	6.67	6.67	6.50	4.83	6.00	5.17	6.33

Participants Feedback: Each participant was asked to score their agreement with specific statements (see Table 4) related to their experience during the trial. The score followed a Likert scale (Joshi, Kale and Chandel) from 1 strongly disagree to 7 strongly agree with, with 4 being neither agreeing nor disagreeing with the statement. The six statements, individual participant scores, and averaged score are provided in Table 5. From the collected feedback, participants felt that PERCEPT-V was easy to learn how to use and easy to use. They thought that the user interface is clear and provided sufficient re-orientation information when they were lost in the Campus Center. Using PERCEPT-V participants felt strongly that they would reach their destination. There were no negative responses given for any of the statements. One interesting observation from the feedback is that participant **P5** and **P7** average score was at least a full point lower than the others. Both participants owned an Android smartphone and were unfamiliar with Voiceover. Moreover, participant **P7** shared that they do not use a smartphone in their daily life. Each participant was asked if they would use PERCEPT-V in the future if it was available to them and they all responded yes.

There are some disadvantages to vision-based localization such as localization in environments that do not have sufficient features and in self-similar areas (e.g. identical floors in a building). To solve these issues we can deploy BLE sensors, which will help us determine distinct zones in the environment. We estimate that for this purpose we need to deploy a few sensors compared to a large number of sensors required to perform accurate sensor-based localization.

Conclusions

This paper presents PERCEPT-V indoor navigation system for blind and visually impaired users. PERCEPT-V uses vision-based localization and provides users through an iOS mobile application continuous navigation instructions which verbally guide the user to the chosen destination. We tested the system with 9 BVI subjects. All subjects were able to reach the destination using PERCEPT-V. PERCEPT-V significantly reduces the cost of deployment and maintenance in the physical environment since only a few sensors (e.g. BLE sensors) may need to be deployed in self-similar and featureless environments. Therefore, there are substantial cost savings for the venue owners compared to systems that use only BLE based localization which requires dense BLE sensor deployment.

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