Guiding Blind Pedestrians in Public Spaces by Understanding Walking Behavior of Nearby Pedestrians

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We present a guiding system to help blind people walk in public spaces while making their walking seamless with nearby pedestrians. Blind users carry a rolling suitcase-shaped system that has two RGBD Cameras, an inertial measurement unit (IMU) sensor, and light detection and ranging (LiDAR) sensor. The system senses the behavior of surrounding pedestrians, predicts risks of collisions, and alerts users to help them avoid collisions. It has two modes: the *"on-path"* mode that helps users avoid collisions without changing their path by adapting their walking speed; and the *"off-path"* mode that navigates an alternative path to go around pedestrians standing in the way. Auditory and tactile modalities have been commonly used for non-visual navigation systems, so we implemented two interfaces to evaluate the effectiveness of each modality for collision avoidance. A user study with 14 blind participants in public spaces revealed that participants could successfully avoid collisions with both modalities. We detail the characteristics of each modality.

CCS Concepts: • **Human-centered computing → Accessibility technologies**; • **Social and professional topics →** *People with disabilities.*

Additional Key Words and Phrases: Visual impairments; pedestrian avoidance; collision prediction; blind navigation; audio interface; tactile interface.

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1 INTRODUCTION

Blind people face significant risks of collision with other pedestrians when walking through public spaces due to their lack of vision. According to one survey, 87.8% of blind people have collided or nearly collided with pedestrians, bicycles, and other obstacles [51]. Using a white cane is the most common method for the blind to sense obstacles and pedestrians, but it requires a user to risk their safety to physically contact the object. Therefore, blind people report that the cane is not useful in avoiding contact with walking pedestrians in crowded

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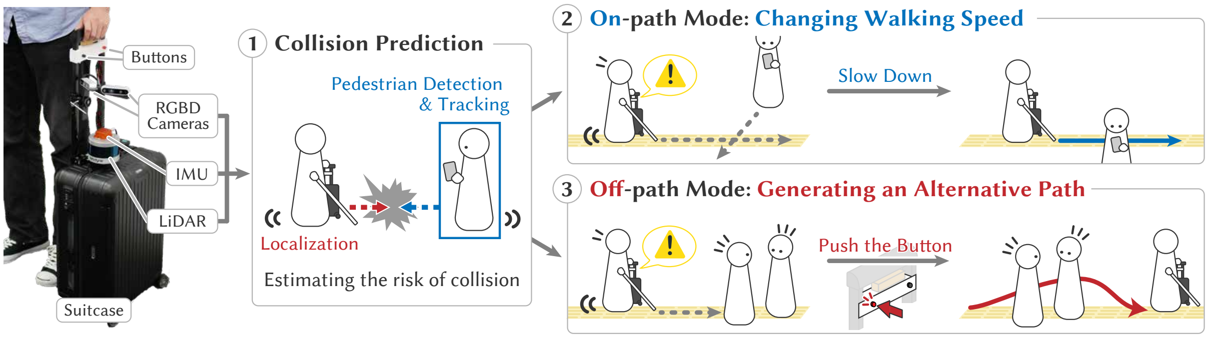

Fig. 1. Overview of the proposed system. 1) The system predicts the potential risks of collisions using two RGBD cameras, a LiDAR sensor, and an IMU sensor. Then, when the system detects a risk of collision, it emits low-urgency alert signals. 2) Blind users who receive these alert signals can avoid a collision by changing their walking speed. In addition, 3) when pedestrians are blocking the user's path, the system emits high-urgency alert signals continuously. If the user pushes the button equipped on the suitcase, our system generates a path around the blocking pedestrians and guides the user safely around them.

sidewalks and corridors or in other crowded environments [74]. Due and Lange reported that blind pedestrians rely on the collision avoidance behaviors of sighted pedestrians, such as changing trajectory or stopping [16]. That is why collision incidents happen when sighted pedestrians have difficulty noticing blind pedestrians in public spaces such as stations [1] and airports [34].

Meanwhile, sighted pedestrians continuously adapt their speed and direction using their sense of vision to make their walking seamless with nearby pedestrians [49]. We characterize such walking behaviors as two types of avoidance behavior: (1) *"on-path"* avoidance: adjusting walking speed without changing the path; and (2) *"off-path"* avoidance: changing the path and walking through free space. For example, sighted pedestrians choose the on-path avoidance when other pedestrians *will* cut across in front, but choose the off-path avoidance when people are standing still in front and talking. Our goal in this work is to enable blind people to walk seamlessly with nearby pedestrians by using the on-path and off-path avoidance, like sighted pedestrians. We argue that the on-path avoidance is more important for blind people because they have to walk along non-visually sensible landmarks. Changing their path frequently may risk them losing their way and becoming disoriented.

Research using computer vision has aimed to assist blind pedestrians to avoid obstacles or hazards [5, 11, 26, 41, 42, 57, 73, 74, 81]. These systems generate an alternative path around the detected obstacles and navigate blind users. However, these systems provide only the off-path avoidance, rather than the on-path avoidance. BBeep is a sonic collision warning system to alert nearby sighted pedestrians about potential risks of a collision via beeping sounds [34]. The system assumes sighted pedestrians will give way to blind users, and a guiding system to help blind people walk seamlessly with nearby pedestrians has not been explored.

We present a guiding system to help blind people walk in public spaces by adapting their walking speed to avoid collision with approaching pedestrians (the on-path avoidance) and by enabling them to avoid standing pedestrians (the off-path avoidance). The system first predicts the risks of collisions using sensors, and then it recommends that the blind user adjust his or her walking speed to avoid a collision with a walking pedestrian or take an alternative route to avoid a collision with a standing pedestrian. For example, if a pedestrian is going to cut across in front of a blind user, the system recommends adjusting the blind user's walking speed. This is called the *"on-path mode."* If a group of people is blocking the blind user's path, the system recommends an alternative route and navigates the user. This is called the *"off-path mode."*

To realize the on-path and off-path modes, our system predicts the risks of collisions with nearby pedestrians. Our system first localizes the user's position and calculates the user's velocity using simultaneous localization and mapping (SLAM) with a light detection and ranging (LiDAR) sensor. The system uses two RGBD cameras to capture a wide field of view and detects surrounding pedestrians by applying a convolutional neural network (CNN)-based object detector from the data on the two cameras. Then, the system can accurately track and predict the motion of multiple pedestrians by compensating for camera motion using the SLAM results. By combining these sensing results, the system predicts the potential risks of collision (Figure 1 (1)). When the system detects a risk of collision, the on-path modes emit low-urgency alert signals for the users. By walking slowly or stopping while being alerted, the users can avoid collisions without changing their path. (Figure 1 (2)). When someone is blocking the blind user's path, the system continues to emit high-urgency alert signals (Figure 1 (3)). In such situations, the off-path mode can be initiated by the user, and the system generates an alternative path to avoid the collision with the standing pedestrian. We designed the system to be attached to everyday luggage like a rolling suitcase. We attached two cameras and a LiDAR sensor to the bar of the handle on a suitcase and asked blind users to carry it. This rolling suitcase form-factor is used as a supportive system for blind people in a recent work [34]. This suitcase-based system has several advantages such as it can capture images without significant motion-induced blur and can carry sensors and computational resources easily [34] (other advantages are described in 3.4.).

Navigation technologies for blind people commonly use an audio interface [2, 3, 8, 13, 18, 50, 52, 57, 59, 64, 65, 77] or tactile interface [4, 62, 74, 78]. Each interface has its own characteristics. For example, audio interfaces can convey clear instructions, but they may block ambient sounds that blind people often use to ensure their safety [10]. Although tactile interfaces may not block these ambient sounds, they have difficulty conveying detailed information. Because of these characteristics, blind users' preferences depend on the types of tasks and environments (*e.g.*turn-by-turn navigation, collision avoidance, indoor/outdoor navigation, and crowded/empty spaces). In this paper, we present our implementation of tactile and audio interfaces to find out which is more suitable for our target situations with our guiding system. The audio interface alerts the risks of collisions by using beep sounds and guides the user by using text-to-speech feedback through a bone conduction headset. The tactile interface warns of the risks of collisions with a vibrating handle and navigates users with a newly developed directional lever, which shows the correct direction. We attached the two tactile devices to the handle of the suitcase.

We conducted a user study with 14 blind people in specific routes and evaluated the effectiveness of the audio and tactile interfaces and the overall guiding system. We obtained the following results.

- Most blind participants successfully avoided the walking and standing pedestrians in both controlled and real-world environments by using both interfaces.
- The sound-based audio interface for the on-path mode made it easier for blind participants to recognize alerts from the system than the vibration-based tactile interface. One reason was that the vibration was affected by the floor texture.
- Participants completed tasks using the tactile interface (the directional lever) for the off-path mode significantly faster than they did using the speech-based audio interface.

Overall, participants had significantly stronger preferences for the tactile interface after the studies. The audio interface was useful in certain situations, but its tendency to block ambient sounds was a major drawback.

2 RELATED WORK

2.1 Blind Navigation Systems

Previous research presented various types of blind navigation systems [3, 4, 13, 18, 24, 44, 50, 52, 59, 65, 80]. Most of these systems use turn-by-turn navigation to help blind users get to their destination with the help of localization technologies, such as a global positioning system (GPS) [52, 59], radio frequency identification (RFID) tags [4, 13, 19], visible light communication [50], and Bluetooth low-energy beacons [3, 15, 35, 65]. While these systems focus on navigating users to their destination, other systems enable avoiding obstacles during navigation. For example, NavCog can convey possible obstacles that are registered on a map [66]. However, it does not help users avoid dynamic obstacles, such as pedestrians, or temporal obstacles, such as carts and signboards.

2.2 Obstacle Avoidance Systems

Obstacle avoidance systems are developed using various types of sensors, such as lasers [38], ultrasonics [32, 67], phone speakers and microphones [72], or depth sensors [11, 21, 26, 29–31, 41, 53, 79]. Some of these systems present all the information detected by the systems, such as the distance and the types and sizes of objects. Users have to avoid obstacles on the basis of such information by themselves. When several obstacles are present, understanding the situation and avoiding them may be difficult, so the path necessary to avoid obstacles must be generated. Some systems plan a path around detected obstacles and navigate users using different interfaces, such as sound feedback [42, 57, 81], a cane connected to a wheeled robot [73], a mobile robot [26], or a leashed aerial robot [5]. Guerreiro *et al.* proposed an autonomous suitcase-shaped navigation robot, CaBot, that guides blind users to a destination [26]. CaBot can avoid static obstacles such as a standing person by changing the user's path. However, these systems mainly focus on static obstacles and support avoiding obstacles only by changing a user's path (off-path avoidance). Avoiding walking pedestrians just by changing walking speed (on-path avoidance) has not been explored in any previous research.

One common assumption is that sighted people will notice the presence of blind people and avoid colliding with them. However, sighted people who are distracted by looking at smartphones or by talking with others are at serious risk of colliding with blind people. To overcome this problem, BBeep was created to help blind people avoid collisions with sighted pedestrians by using a suitcase-shaped system [34]. When the system detects risks of collisions, it plays alert sounds to surrounding people. The drawback is that the sounds may attract too much attention from these people. It may cause a disruptive situation because they will need to clear a path immediately.

2.3 Non-Visual Interfaces for the Blind

2.3.1 Audio Interfaces. Audio interfaces are used in existing blind navigation systems for conveying both turn-by-turn navigation commands and obstacle avoidance paths. Natural language is mainly used for navigation commands [3, 18, 35, 64, 65]. Non-speech sounds are also used for navigation, for example, 3D spatialized audio cues are used for indicating turning directions [8, 77], and sound patterns are used for determining correct directions [2, 57]. Audio interfaces can provide clear information that is easy to learn. However, blind people often depend on ambient sounds to ensure their safety, and the audio commands may disrupt their hearing ability.

2.3.2 Tactile Interfaces. Tactile interfaces have been developed to overcome or supplement the limitations of audio interfaces. Previous research used vibration patterns to indicate approximate turning directions [62, 78]. Shape-changing interfaces have been used to indicate fine directions. Animotus [69] is a cube-shaped interface that conveys heading directions when its top-half is rotated. Animotus was evaluated by blind participants, and they were able to follow a route provided by using the device [70]. Audio and tactile modalities have their own characteristics, and the efficiency of each interface depends on the tasks and environments. Some research showed that blind users prefer tactile-based navigation because they can focus on ambient sounds [47], and other studies showed that blind users preferred an audio interface because they do not need additional wearable devices [60]. On the basis of this previous work, we designed audio and tactile interfaces and evaluated their effectiveness.

3 GUIDING SYSTEM FOR A PUBLIC SPACE

Our main goal is to develop a guiding system to help blind people and to make their walking seamless with nearby pedestrians in public spaces. Such public spaces are characterized by *"restricted, impeded, and unstable flow* of pedestrians in the levels of services defined by Polus *et al.* [55]. In this section, we describe the design of our guiding system specifically for the following typical situations: *A blind pedestrian tries to walk through a public space such as public buildings and shopping centers. He/she is familiar with the route. He/she should be able to walk seamlessly with the surrounding pedestrians.*

- **Situation 1)** Other pedestrians often cut across the blind pedestrian's path at close range with average walking speed (1 – 1.5 m per second). Such pedestrians can be regarded as dynamic obstacles for him/her.
- **Situation 2)** A group of standing pedestrians blocks the blind pedestrian's path unintentionally. Such pedestrians can be regarded as static obstacles for him/her.

3.1 On-path Navigation

Blind pedestrians are usually trained to walk along specific familiar routes with non-visual landmarks given that they lack vision. We argue that a system should stick to these familiar paths as much as possible even when it navigates the blind pedestrian so as to avoid collision. We call such navigation without route-changes *"on-path"* navigation. In Situation 1, the system should recommend adjusting the blind user's walking speed without changing his or her path to avoid a collision. The technical challenge is creating a method to present such alerts in real-time. Therefore, we designed two interfaces: a sound-based audio interface and a vibration-based tactile interface based on previous work [7, 17, 27, 40, 45, 54, 56, 63]. The system first senses the walking speed and direction of the approaching pedestrian and predicts the trajectory and the risks of collisions. Then, the system alerts the user to adjust his or her walking speed to avoid a collision with a walking pedestrian (see Implementation).

3.2 Off-path Navigation

In Situation 2, the system needs to help a blind pedestrian avoid obstacles by having him or her move out of the path, walk through free space, and return to his or her path. Successfully navigating a user accurately along a target path by continuously presenting directions is a challenge, but previous studies showed that audio and tactile interfaces may have sufficient utility for such a situation [20, 69, 70]. Therefore, we designed and compared both interfaces. The speech-based audio navigation was designed on the basis of previous methods like Headlock [20]. A new shape-changing device to indicate the accurate direction in real-time was designed on the basis of previous research [69, 70]. We call the device the *"directional lever"* (see Implementation and Figure 3 (2)).

3.3 Attachment Design

We designed the system as a set of components attachable to a standard rolling suitcase (Figure 1). Given the footprint of the required sensors, it will be difficult to make the system fully wearable in the near future. As an alternative, we expect such a system can be attached to daily mobile devices, such as a rolling suitcase, a shopping cart, and a wheelchair. Such a rolling suitcase with attachments can move naturally alongside a blind person, much like a guide dog or a sighted guide who walks side-by-side. Kayukawa *et al.* created a supportive system for blind people [34] and argued that this rolling suitcase form has four advantages: 1) for a blind user, a rolling suitcase can often act as an extended sensing mechanism for identifying changes in floor texture or as a form of protection from collisions with obstacles; 2) as a robotic sensing system, it also provides a convenient place to store and attach sensors, power, actuators, and computing resources; 3) users can walk with the system easily on flat spaces; and 4) the system can capture images without significant motion-induced blur. For these reasons, we also chose a suitcase form for our prototype system.

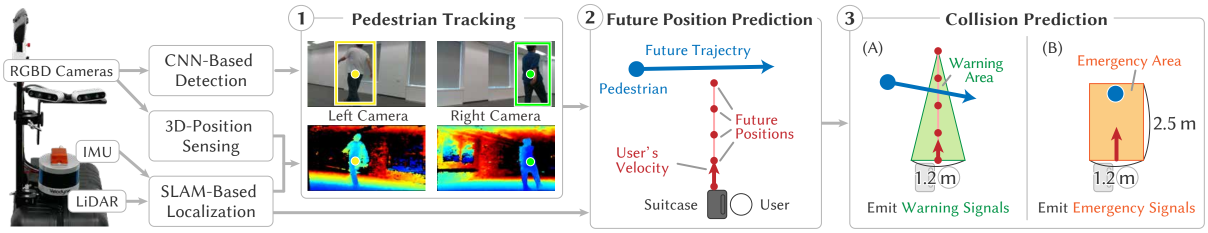

Fig. 2. Overview of the on-path mode. 1) The system detects and tracks the pedestrians' position using two RGBD cameras and the SLAM-based localization method. 2) The system estimates the user's current position and velocity using the SLAM results and then predicts the user's future position. Next, 3) the system estimates two levels of collision risks and emits two types of alert signals (A: a warning signal and B: an emergency signal) via an audio or tactile interface.

3.4 Navigation Interface Overview

The overview of the navigation process is as follows (see Figure 1). A blind user usually starts walking with the on-path mode. The user is instructed by the system to slow down when he or she perceives alert signals, sounds, or vibrations. The user can walk at normal speed again after the alert signal stops. This means the user's path is clear and safe. If a pedestrian is not aware that the user is approaching and blocks the user's path, the system continues to emit alert signals. In such a situation, a user can push the start button on the handle to enable the off-path mode to avoid the standing pedestrians. The system automatically navigates the user in speech or with the directional lever. After returning to the user's usual path, the system automatically changes back to the on-path mode.

4 IMPLEMENTATION

In this section, we first describe our implementation of the system, which is characterized by its on-path and off-path modes, followed by the audio and tactile interfaces, respectively.

4.1 The On-path Mode

As shown in Figure 2, we attached a LiDAR sensor, an inertial measurement unit (IMU) sensor, and two RGBD cameras to a suitcase. The system uses these sensors to predict the risks of collisions. In what follows, we explain how the system predicts the risks of collision on a step-by-step basis.

4.1.1 Localization. During navigation, our system estimates the current location and direction of a user using a cartographer package[1] [28] of the robot operating system (ROS) [58]. The cartographer can localize by comparing the 3D pointcloud map previously generated and real-time scanning data from the LiDAR and IMU sensors. On the basis of the localization results, the system estimates what the user's velocity and position will be four seconds in the future (Figure 2 (2)).

4.1.2 Pedestrian Detection, Tracking, and Prediction. We use two RealSense D435 cameras[2] for tracking pedestrians to obtain a wide field of view. Each camera has an 69.4° × 42.5° field of view. By arranging the two cameras horizontally (Figure 2 (1)), we can obtain about a 135° × 42.5° field of view. To calibrate the relative position and orientation of each camera for LiDAR, we used an intensity-based LiDAR camera calibration tool [75]. Pedestrians are tracked using the following steps.

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[1] http://wiki.ros.org/cartographer

[2] https://www.intelrealsense.com/depth-camera-d435/

1. The system detects pedestrians using a YOLOv3 object detector [61]. The model is trained for detecting people using the publicly available COCO dataset [43].
2. The system calculates the positions of detected pedestrians in camera coordinates. RGB-D images are used to calculate the 3D positions of the detected pedestrians in the camera coordinates.
3. The system calculates the positions of detected pedestrians using map coordinates. By using localization results, it compensates for camera motion and converts pedestrian positions into map coordinates from the camera coordinates.
4. The system matches detected pedestrians with tracked pedestrians. To match the detected pedestrians with the tracked pedestrians, we first use a Kalman filter [33] for each track to predict the positions in the next time step. We assume each person has a 1.0m circle size in the 2D map and calculate the intersection over union (IoU) for the detected and predicted circles. To find the best matches of tracked circles and detected circles using the IoU, we use the Hungarian algorithm [37].
5. The system estimates the velocity for each tracked pedestrian using a Kalman Filter.

These steps for detection (steps 1–3), tracking (step 4), and velocity estimation (step 5) are done using separate processes. The detection steps are done for each camera, and the detection results for each camera are merged in the tracking step. All these steps were done at about 4–5 FPS when we used a laptop computer (Intel Core i7-8750H CPU @ 2.20GHz, NVIDIA GeForce GTX 1080 Mobile GPU). On the basis of the estimated surrounding pedestrians' velocity, the system assumes that the pedestrians move at the constant velocity and predicts their positions four seconds in the future (Figure 2 (2)).

4.1.3 Collision Prediction. The system predicts the risk of a future collision on the basis of all the predicted positions of surrounding pedestrians and the blind user, then it decides whether or not to emit an alert signal. A collision is expected when a pedestrian's future trajectory crosses the "Warning Area" shown in Figure 2 (3) A. The system defines the area as triangular, its base length is $1.2m$, and the apex position is the user's predicted position in 4 seconds. The system can dynamically change the "Warning Area" in accordance with the user's velocity. For example, when the user is walking faster, the system predicts collisions with pedestrians in a larger area. When the user is walking slower, the system considers collisions in a smaller area. If the system detects the intersection between the pedestrian trajectory and the warning area, the system decides the user has a risk of collision and emits the low-urgency alert signals. In addition, we define the "Emergency Area" shown in Figure 2 (3) B. The system defines the area as a fixed-size rectangle, $1.2 \times 2.5m$. When a pedestrian is in the area, the system emits the high-urgency alert signals. In this case, we expect the blind user to stop immediately. The system estimates the risk of collisions in the "Emergency Area" by assuming that both the suitcase and the user face the same direction. Thus, in our user study, we asked blind participants to walk while keeping the suitcases in the direction they were heading.

4.2 The Off-path Mode

4.2.1 Path Planning. To navigate a user in the off-path mode, the system assumes that navigation maps include route information that is safe for blind users. In the following user studies, we assumed that the floor map had the positions of the tactile paving. Note that this study focused on navigating users on tactile paving, but other non-visual sensible landmarks, such as walls, can be used to define the blind users' path.

To enable users to avoid standing pedestrians, the system sets the current user's position as the start position of the off-path mode, and it sets the position five meters ahead of the user on tactile paving as the goal position of the off-path mode. Then, the system plans a path to avoid the pedestrian(s) and return to the tactile paving. The path planning can be done with the navigation packages of the ROS, Navfn global path planner[3], and DWA

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[3] http://wiki.ros.org/navfn

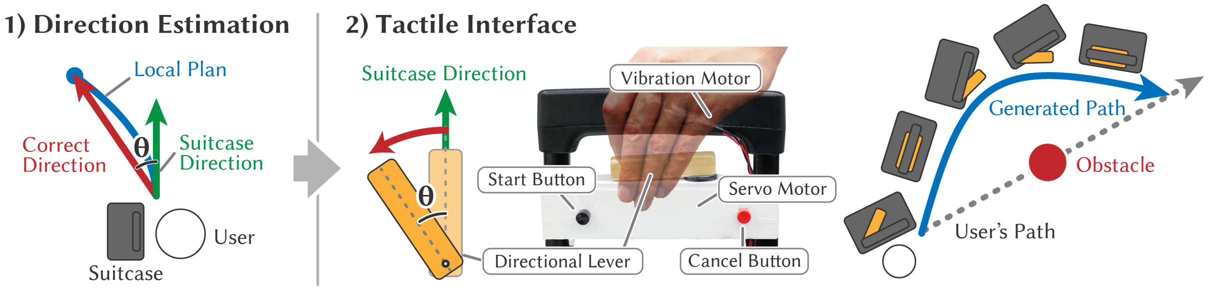

Fig. 3. 1) In the off-path mode, our system calculates the angle (θ) between the correct direction and the suitcase direction. 2) The tactile interface has two vibration motors and a directional lever driven by a servo motor indicating the correct direction. The directional lever tells the user the correct walking direction in accordance with the generated path in the off-path mode.

local path planner[4] [22]. Navfn can generate a safe path avoiding obstacles such as pedestrians, walls, and static obstacles using surrounding structural information from the LiDAR sensor. When the system cannot generate a safe path, for example, in cases where no space is available for pedestrian avoidance, the system continues to emit the emergency alert to stop the blind user until a path becomes available.

4.2.2 Direction Estimation. Until the user reaches the defined goal position, the DWA local path planner shows a local plan with the trajectory that the user should follow at that moment. Our system uses the local plan to estimate the correct walking direction (θ in Figure 3 (1)). The correct direction is defined by a straight path to the end of the local plan. To guide blind users in the correct direction, the system calculates the angle between the correct direction and the suitcase direction estimated by the SLAM.

4.3 Interface for Navigation Instruction

4.3.1 Audio Interface. Our audio interface emits beeps to alert the user about the risk of collisions. We use a bone conduction headset to convey navigation information without impeding environmental sounds. Beeps have been used as a means to alert people about urgent situations, such as in aircraft [9], nuclear power plants [46], and hospital intensive care units [48]. Audio notifications can also alert drivers of an imminent risk of collision or assist in navigation [45]. The relationship between perceived urgency and sound parameters is well documented [17, 27, 45]. We prepared two types of beeps with different urgency levels denoted low and high. Specifically, we varied the pulse rate, the pitch, and the base frequency, as given in Table 1. The values we used are based on previous research addressing sound urgency [34, 54, 63].

In the off-path mode, the audio interface instructs the user on the correct walking direction via text-to-speech feedback such as *"Right," "Left,"* and *"Go straight."* These navigation commands were used in a prior navigation system called Headlock [20], which provides information to navigate toward detected objects (*e.g.*, direction and distance) via audio. We chose such simple navigation commands because a previous study revealed that blind people have difficulty adjusting their orientation slightly [66]. Our audio interface says *"Right"* or *"Left"* depending on the angle between the correct direction and the suitcase direction. When the absolute value of the angle is within 10 degrees, the system says *"Go straight."* These speech commands are emitted at one-second intervals.

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[4] http://wiki.ros.org/dwa_local_planner

Table 1. Feedback patterns. PD: Pulse duration, IPI: inter-pulse interval, and BF: base frequency.

Interface	Urgency Level	PD	IPI	BF
Audio	Low	0.5 s	0.5 s	400 Hz
	High	0.1 s	0.1 s	1000 Hz
Tactile	Low	0.5 s	0.5 s	N/A
	High	Inf	N/A	N/A

4.3.2 Tactile Interface. To provide vibration feedback in the on-path mode, we attached two vibration motors (T.P.C., FM34F), which were connected to an Arduino Uno Rev3[5] on a suitcase handle (Figure 3 (2)). Studies have used vibration to alert people of emergency situations [25, 74], and the relationship between perceived urgency and vibration parameters has been shown [7, 40, 56]. Specifically, perceived urgency significantly decreases as the inter-pulse interval (IPI) increases. On the basis of previous research [7, 40, 56], we designed a low-urgency tactile signal that has an IPI and a high-urgency tactile signal that causes continuous vibrations (Table 1).

In the off-path mode, the system needs to convey the correct direction to avoid obstacles. The tactile interface has also been used to show directions to destinations [14, 47, 62, 68]. We designed the *"directional lever,"* which always indicates the correct direction (Figure 3). The directional lever is rotated by a servo motor (NEW TC, SE-A410) that is connected to an Arduino Uno Rev3. We attached the directional lever under the suitcase handle. As shown in Figure 3 (2), a user holds the suitcase handle with one hand and clamps the directional lever with the fingers. While the suitcase is facing the correct direction, the directional lever indicates ahead. When users should turn right (left), the lever indicates right (left) in accordance with the angle of the estimated correct walking direction (θ in Figure 3 (1)). For comfortable use, we clipped the angle range of the directional lever from -30° to 30°.

5 USER EVALUATIONS

We conducted a user study with 14 blind people. The main goals were 1) to evaluate if participants could avoid collisions using our guiding system, and 2) to evaluate the effectiveness of the tactile and audio interfaces. We asked the participants to walk a short route in a controlled environment and to walk a long route in a real-world environment.

5.1 Participants

As shown in Table 2, we recruited 14 blind participants (6m/8f) with ages ranging from 32 to 70 (Mean=50.43 and SD=10.04). Thirteen participants (P1–P13) regularly used a white cane, and one (P14) owned a guide dog. They considered themselves to have good orientation and mobility skills.

5.2 Tasks

In this study, we asked the participants to walk on tactile paving located in two types of environments: 1) controlled environments where one experimenter crossed or blocked a blind user's path, and 2) real-world environments where many different people were walking. The participants walked through these environments with either the audio or tactile interface.

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[5] https://store.arduino.cc/usa/arduino-uno-rev3

Table 2. Demographic information on our participants and the SUS Score for each interface.

Demographic information				SUS Score (Grade)			
ID	Gender	Navigation Aid	Age	Audio		Tactile	
P01	Female	Cane	44	85	A+	77.5	B+
P02	Male	Cane	56	82.5	A	82.5	A
P03	Male	Cane	48	90	A+	92.5	A+
P04	Female	Cane	47	67.5	C	62.5	D
P05	Female	Cane	48	72.5	C+	72.5	C+
P06	Female	Cane	57	65	C	65	C
P07	Female	Cane	51	87.5	A+	87.5	A+
P08	Female	Cane	43	45	F	52.5	D
P09	Male	Cane	40	72.5	C+	75	B
P10	Male	Cane	70	57.5	C	47.5	F
P11	Female	Cane	32	77.5	B	70	C
P12	Male	Cane	55	75	B	72.5	C+
P13	Male	Cane	69	90	A+	95	A+
P14	Female	Dog (primary) and Cane	46	97.5	A+	97.5	A+
		Mean	50.43	76.1	B	75.0	B
		SD	10.04	13.7		14.6	

5.2.1 Controlled Environments. To evaluate the effectiveness of our system in the same conditions across all participants, we first prepared a controlled environment that had a simple route of 16 meters with tactile paving. In that environment, one experimenter interrupted participants' walking. We prepared two conditions to evaluate the effectiveness of the on-path and off-path modes (see also Figure 4 (1)): A) one experimenter walked across the route at two points, and B) one experimenter blocked the tactile paving at two points. We asked the participants to walk the route four times (two interfaces × two conditions). In condition A, the experimenter started walking at the time at which they would collide with the participants. Each participant held the suitcase handle with one hand and used his or her white cane with the other. Their goal was to walk on the tactile paving while avoiding collisions with the experimenter. Participants started each task without knowing how the experimenter would behave (walk across or block their path). We asked participants to change modes on the basis of the feedback from the system.

5.2.2 Real-world Environments. In the study, we also asked blind participants to walk a long route (approximately 180 meters) on the ground floor of an office building (Figure 4 (2)). We selected this real-world environment because people constantly walk into or out of the office, restroom, convenience store, coffee shop, etc. When participants walked on the route, one experimenter crossed the participants' path at two points and blocked the path at one point (Figures 4 (2) and 5). Participants walked the long route twice using either the audio or tactile interface.

5.3 Procedure

We first provided an overview of the study and administered a questionnaire on demographics and navigation habits. We also surveyed the participants' opinions about using a headset to receive navigation instructions while

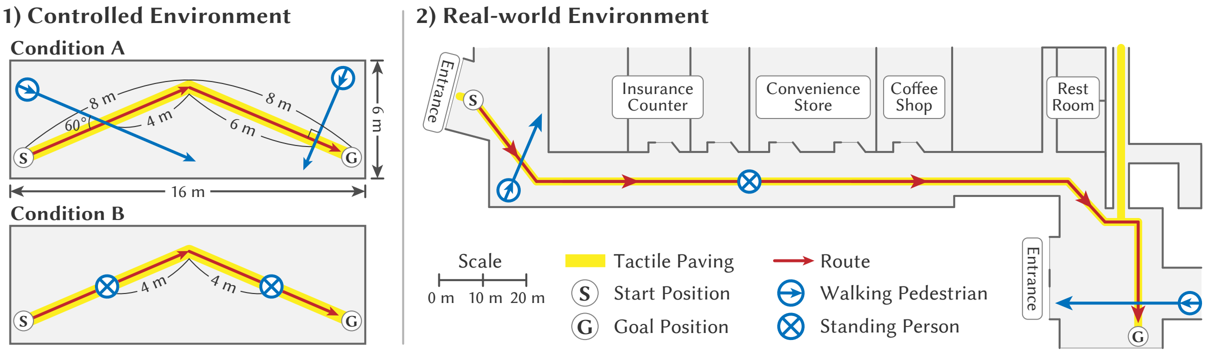

Fig. 4. The routes used in our user study. 1) We first asked the participants to walk routes in a controlled environment. The routes included condition A, where an experimenter crossed the participants' route at two different points, and condition B, where an experimenter blocked the route at two different points. 2) Blind participants also walked a long route (around 180 meters) in a real-world environment. The route included two points where an experimenter crossed the participants' route and one point where an experimenter blocked the route.

walking alone. Next, we described the two modes for two types of interfaces to the participants and gave them a short training session (10 – 20 minutes) until they became familiar with each interface. We adjusted the volume in the audio interface to make sure it was comfortable but audible. During the training session, we explained how to hold the suitcase as it affects the accuracy of collision prediction.

For the first task, we asked the participants to walk the short route in the controlled environment while using either the audio or tactile interface. They walked the route four times while changing the interfaces and conditions (conditions A and B shown in Figure 4 (1)) in a counter-balanced order. For each trial, we measured the task completion time and counted the number of collisions between the participants and the experimenter. After completing the first task, participants took a post-questionnaire, which was audio recorded for further analysis. Specifically, we asked the participants to rate the following sentences using 7-point Likert items (rating from 1: strongly disagree to 7: strongly agree):

Q1: *"The on-path mode with audio interface helped me avoid collisions while changing my walking speed.*[6]*"*
Q2: *"The on-path mode with tactile interface helped me avoid collisions while changing my walking speed."*
Q3: *"The off-path mode with audio interface helped me avoid pedestrians who blocked my path."*
Q4: *"The off-path mode with tactile interface helped me avoid pedestrians who blocked my path."*

We also asked open-ended questions about the advantages and challenges of each interface.

The remaining tasks were performed in the real-world environment shown in Figures 4 (2) and 5. The participants had a training session to walk the route twice while using each interface to grasp the overall route. Then, they were again asked to walk the route twice while using either the audio or tactile interface. In each trial, we did not instruct the participants to use a particular mode. Instead, we asked them to change the modes by themselves on the basis of the alerts from the system. We informed the participants that a researcher would be walking behind them to guarantee their safety as well as other pedestrians' safety (Figure 5). The researcher did not intervene unless an imminent risk or a deviation from the path occurred. We counted the number of times imminent risks of collisions occurred for each condition. To observe the participants' movement and the response of pedestrians, we mounted a GoPro camera on the top of the suitcase during the study.

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[6] All of the communications with participants were done in their native language. In this paper, we describe any translated content in the form of "*translated content*".

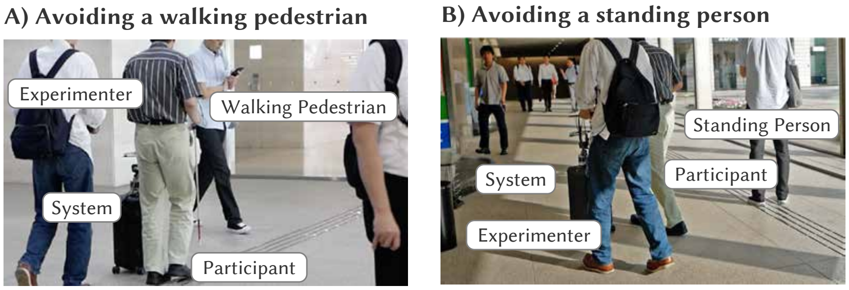

Fig. 5. User study of a real-world environment. Participants walked on tactile paving while avoiding a walking experimenter (A) and a standing experimenter (B). One experimenter crossed the participants' path at two points and blocked the path at one point.

After completing all the tasks, participants took a post-questionnaire. The participants were again asked to rate the four sentences (Q1–Q4) they assessed after the first task in the controlled environment. In addition, we asked them to rate the following sentences about their preferred interface using 7-point Likert items (rating from 1: do not prefer to 7: prefer):

Q5: *"I prefer the audio interface for navigation instructions."*
Q6: *"I prefer the tactile interface for navigation instructions."*

They also rated the items of the system usability scale (SUS) [12]. Finally, we asked open-ended questions to gather feedback about their overall experience with each interface. The task process took around 45 minutes, while the whole experiment took approximately 90 minutes per participant.

6 RESULTS

6.1 Audio Interface Usage

All participants commented that receiving auditory navigation commands via headsets is undesirable because these commands may interfere with ambient sounds. For that reason, 11 participants out of 14 mentioned that they never use a headset while walking: A1: *"When I'm walking alone, I always listen to various sounds such as footsteps and engine sounds. A headset may block these sounds, so I always walk without using one."* (P3); A2: *"When I use a headset to get navigation instructions, I always keep in mind that I need to stand in a safe zone, such as near a wall. If I receive auditory commands while walking through public spaces, I am distracted by these commands and have difficulty hearing ambient sounds."* (P9); A3: *"I sometimes use Google Maps and a headset to get instructions to the destination. While using the app, I make sure I stop walking."* (P5); and A4: *"When audio commands come from a headset, I tend to concentrate on listening to them. In fact, I was once nearly hit by a car when I tried walking with a headset."* (P10). Although seven participants (P5–P7, P9, P11–P13) mentioned that they sometimes use audio-based navigation systems, such as Google Maps, they also strongly agreed on the risk of using a headset while walking. In particular, three participants (P5, P7, and P9) mentioned that they stop walking while listening to audio commands from a navigation app.

6.2 Experience of Collision with Nearby Pedestrians

Thirteen participants out of 14 mentioned that they have collided or nearly collided with pedestrians in public spaces. The only exception was P14, who commented that her dog was very well trained at avoiding collisions. All participants except P2 and P14 also mentioned that they had experienced situations in which someone had

Table 3. The number of times the system emitted a warning or emergency alert.

Interface	Mean and SD	
	Warning Alert	Emergency Alert
Audio	12.6±5.7	4.1±2.2
Tactile	12.5±3.1	8.1±3.6

blocked their path even on a tactile paving. P2 commented that he could recognize empty spaces with no standing pedestrians by listening to the ambient sounds.

6.3 Overall Performance

6.3.1 The Number of Collisions. In our controlled study, all participants reached the goal without collisions. In our real-world study, while participants did not encounter real pedestrians who blocked their path, several pedestrians crossed it. Table 3 reports the number of times the system emitted a warning or emergency alert. The participants were thus at risk of collision about 10 times in each trial. Blind participants could avoid such pedestrians by using the on-path mode. Most participants also successfully avoided the experimenter who crossed the participants' path at two points and blocked it at one point. However, two exceptions occurred. In these cases, participants had an imminent risk of colliding with the standing experimenter, and another experimenter had to ask them to stop. The reasons for these close calls were as follows: 1) P11 and P13 continued to walk without noticing the vibration alerts from the system; and 2) although the system generated a path to the left, the system told P7 to *"go straight,"* because the suitcase was facing the generated path (*i.e.*, a difference occurred between the suitcase direction and the user's walking direction).

6.3.2 Task Completion Time. Table 4 reports the task completion time in terms of its mean and standard deviation, as well as 95% confidence intervals, obtained using each interface. The table also shows the p-value of the Wilcoxon signed-rank test. Our statistical analysis revealed that, in the off-path mode, participants who used the directional lever could avoid a standing person more quickly than those who used the speech-based audio interface. In the on-path mode, we observed no significant differences in the task completion time between the audio and tactile interfaces.

6.3.3 Video Observation. Video recordings enabled us to analyze the behavior of the blind user and sighted pedestrians to complement our quantitative analysis. We observed that participants could switch between the on-path mode and off-path mode on the basis of the feedback from the system. Participants mainly walked with the on-path mode and slowed down or stopped when the system emitted alert signals. When the system continued to emit alerts, they pushed the start button to enable the off-path mode. In the controlled environments, all participants could switch between the on-path and off-path modes successfully. In the real-world environment, many participants also could change the modes properly. However, as mentioned above, P11 and P13 who used the tactile interface continued to walk without noticing the vibration alerts and had an imminent risk of colliding with the standing experimenter.

6.4 Ratings of Our System

Figure 6 shows the participants' ratings: the effectiveness of the on-path mode with the audio interface (Q1) and tactile interface (Q2), the effectiveness of the off-path mode with the audio interface (Q3) and tactile interface (Q4), and the participants' preferences for the audio interface (Q5) and tactile interface (Q6). In the study, we asked Q1–Q4 after participants finished tasks in both the controlled and real-world environments. We compared these

Table 4. Quantitative evaluations of the task completion time: Mean and SD: the mean and standard deviation of the task completion time; Lower and Upper: the lower and upper bounds of the 95% confidence intervals, respectively; and the p-value of the Wilcoxon signed-rank test (* indicates the significance found at the levels of 0.01).

Condition	Audio Interface			Tactile Interface			p-value
	Mean and SD	Lower	Upper	Mean and SD	Lower	Upper	
Pattern A (the on-path mode)	36.3 ± 5.85	32.8	39.8	39.4 ± 8.60	34.3	44.6	0.23
Pattern B (the off-path mode)	59.5 ± 9.97	53.5	65.5	53.6 ± 8.08	48.7	58.4	**0.015***

questions using the Wilcoxon signed-rank test. The p-values of each test are shown in Figure 6. A comparison of answers to each question between the controlled and real-world environments showed a significant difference in Q2. The effectiveness of the vibration-based tactile interface significantly reduced after the participants used it in the real-world environment. In addition, we also observed a significant difference between Q5 and Q6. Our analysis found that participants had significantly stronger preferences for the tactile interface than the audio. In Q6, 12 participants rated the tactile interface higher than neutral on its navigation instructions (over 5 points). We observed no significant differences in the other tests.

Table 2 reports the scores of the system usability scale (SUS) for each participant. The mean (M) and standard deviation (SD) of the SUS score were 76.1 and 13.7 for the audio interface and 75.0 and 14.6 for the tactile interface, respectively. Participants who did not like our system mainly pointed out the difficulties with the suitcase form. We describe the feedback from them in a later section.

6.5 User Feedback on Our System

6.5.1 Overall Experiences. Participants generally agreed that the on-path mode was effective: A5: *"While walking alone, I always concentrate on grasping surrounding environments via auditory sensations to avoid collisions. Using the system alerted me of the risks of collisions, so I could walk more confidently"* (P13); A6: *"The system emits no alert signals when my path is safe. Therefore, I could feel safe walking when no alerts were being emitted"* (P8); A7: *"The system [the on-path mode] told me my path was clear and safe. So, I could walk faster while the system was not emitting alert signals."* (P1); and A8: *"In my workplaces [a braille library and a school for the blind], I sometimes collide with other blind pedestrians. Thus, I want to use the system in my office"* (P11).

We also got positive feedback on the off-path mode: A9: *"When I encounter a group of people who block my path, I always ask them to move out of the way. By using the system, I could avoid such people by myself"* (P12); and A10: *"When I avoid obstacles, I sometimes lose my way and become disoriented. The system [the off-path mode] is useful because it can guide me back to my path"* (P7).

To generate an alternative path in the off-path mode, we used the navigation packages in ROS. The packages are standard for controlling robots, but P7 and P8 commented that the navigation was not smooth enough for human navigation: A11: *"When I avoided pedestrians using the off-path mode, the system sometimes instructed me to alternate between going toward the right and left. Thus, I felt I lost my position and direction"* (P7); and A12: *"In the off-path mode, the system provided me with the same direction repeatedly, and it made me confused"* (P8).

Nine participants provided negative feedback on the suitcase form. We present our examination of this feedback in the discussion section: A13: *"This suitcase-shaped system was too large and heavy for daily use"* (P10); A14: *"When I walk with a cane, I want to keep my other hand free"* (P6); and A15: *"This system is large and I'm afraid of the additional risk of hitting it against other pedestrians, especially in a very crowded area"* (P8). Three participants

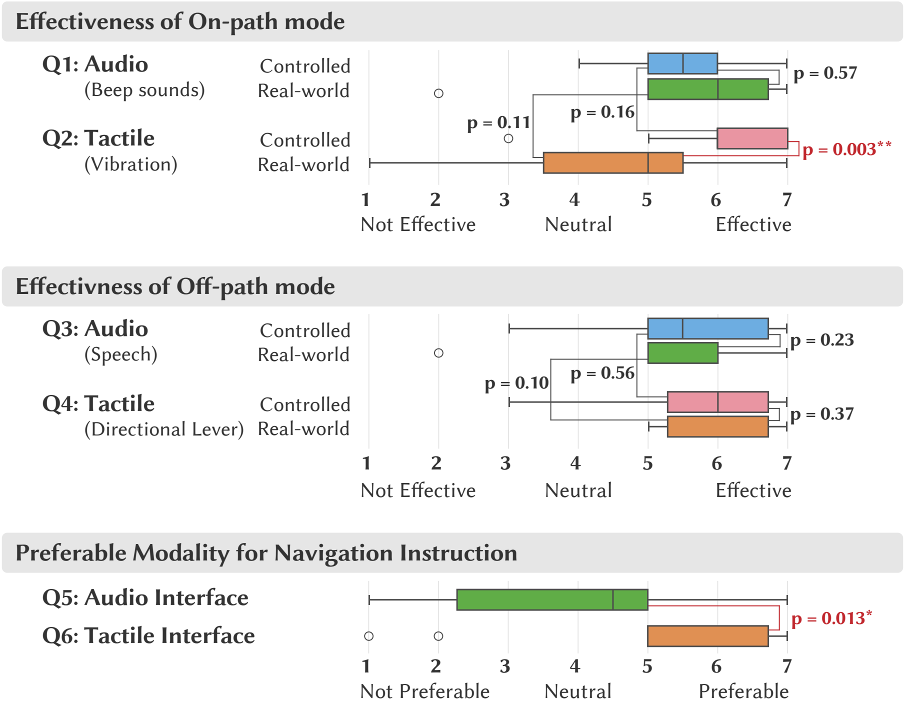

Fig. 6. Box plots of users' ratings (Q1–Q6): Controlled and Real-world are ratings after tasks in the controlled environment and the real-world environment, respectively, and p: p-is the value of the Wilcoxon signed rank test done on each question (* and ** indicate the significance found at the levels of 0.01 and 0.001, respectively).

(P7, P13, and P14) also mentioned the need to shrink the tactile interface: A16: *"If the tactile interface can be attached to my cane, I want to use it every day"* (P13); and A17: *"I'd be so happy if the tactile device were made small and lightweight enough for me to hold it in my hand"* (P7).

6.5.2 Audio Interface. All participants mentioned that the audio feedback was easy to recognize: A18: *"Audio feedback is clearer than tactile feedback. Thus, I could respond to it quickly"* (P5); and A19: *"I could distinguish beep sounds easily because these sounds were characterized by not only the pulse rate but also the pitch"* (P4). However, they also reported that the audio interface was disadvantageous for sensing ambient sounds: A20: *"I walk while getting surrounding information using my ears, so I don't want to use a headset while walking if at all possible. In particular, when I heard auditory instructions through the headset, I had difficulty listening to footsteps"* (P9); A21: *"When I was using the audio system in the quieter environment [the controlled environment], I could easily hear both ambient sounds and audio signals. However, in the noisy environment [the real-world environment] where there are many ambient sounds such as footsteps, it was necessary to use extra awareness to hear ambient sounds"* (P5); A22: *"In the real-world environment, where many people were walking, there was a larger amount of information from ambient sounds than in the controlled environment. So, I had difficulty recognizing both ambient sounds and audio-based feedback"* (P11); A23: *"Text-to-speech feedback distracted me more than beeping sounds"* (P10); and A24: *"The instructions from the system were simple. So, I could distinguish instructions even if I used the tactile system. I think it is excessive to use the audio system to convey such simple instructions"* (P2).

6.5.3 Tactile Interface. All participants appreciated that the tactile interface did not interrupt auditory sensations: A25: *"I could easily grasp the surrounding environment and collision risks by simultaneously using my cane, my ears, and tactile signals from the system"* (P8); and A26: *"Audio-based feedback interfered with my auditory sensations, but I could use both the auditory sensations and tactile-based instructions. The tactile interface gave me an additional sensing modality"* (P11). However, some participants mentioned that the vibration alerts were difficult to recognize: A27: *"I had to distinguish between two vibration patterns by considering the pulse duration, so it was harder than beep sounds with changing pitch"* (P5). In addition, eight participants commented that the effectiveness of the vibration depended on the surface of the floor: A28: *"The ground of the real-world environment had a rough surface, and the handle of the suitcase also vibrated. I had difficulty distinguishing between the suitcase vibration and the vibration alerts"* (P9); and A29: *"[In the real-world environment,] I had to concentrate on recognizing the vibration alerts because the suitcase vibrated due to the unevenness of the floor"* (P6).

The blind users provided positive comments on the directional lever: A30: *"The directional lever helped me adjust the walking direction because it indicated the correct direction directly"* (P8); and A31: *"The lever could tell me the direction more precisely than auditory commands could. If the system were to say precise directions, like 'turn right 32 degrees,' it would be time-consuming and annoying"*; (P3). In particular, all the participants mentioned that the directional lever was effective in both the controlled and real-world environments: A32: *"The directional lever was not affected by the surface of the ground and always worked effectively"* (P7). However, three participants (P1, P2, and P10) mentioned that the navigation lever took time to get used to: A33: *"The directional lever took a while for me to get used to because it indicated the direction too precisely"* (P2).

7 DISCUSSION

7.1 Effectiveness of The Guiding System

Both the controlled and real-world studies showed that our guiding system was effective for blind users to prevent collisions with pedestrians. Most participants successfully avoided collisions with nearby pedestrians by using the on-path and off-path modes properly. Feedback from the participants also supported the effectiveness of our system (A5–A10). They appreciated that our collision warning system enabled them to walk more confidently and with a more secure feeling than they usually do in daily life (A5–A7).

7.2 Audio Interface

We observed that participants listen for ambient sounds to ensure their safety while they walk through a public space. All participants commented that receiving audio feedback frequently while walking in the real-world situation was not usable because it interfered with their ability to make out useful ambient sounds such as footsteps of other pedestrians and echoes from walls (A1–A4, A20–A24). In particular, two participants commented that they did not want to use the audio system in the real-world environment because of the rich ambient sounds they needed to listen for (A21 and A22). Although the participants mentioned that they could recognize the sound alerts more clearly than the vibration alerts (A18 and A19), they had significantly stronger preferences for the tactile interface (Q5 and Q6). This result is understandable since the footsteps and other sounds from other pedestrians are faint and can be easily masked by other ambient sounds or computer-generated navigation commands. In echolocation, changes in frequency and amplitude of low-frequency sounds need to be detected to recognize changes in echoes [36]. Such recognition requires trained abilities, which vary among blind people (see 1. Introduction). From this study, audio interfaces are not a promising interaction method for navigation tasks. We believe more studies should be done to seek better interaction methods for the diverse abilities of blind people by combining audio, haptics, and other non-visual media.

7.3 Tactile Interface

7.3.1 Advantages. We observed two advantages of the tactile interface. First, the users could recognize the vibration alerts and the correct direction indicated by the lever while listening to ambient sounds (A25 and A26). Second, the directional lever enabled the participants to avoid standing pedestrians significantly faster than the speech-based audio interface did. The participants also commented that the directional lever could indicate the correct direction directly (A30 and A31), and all participants commented that the lever was not affected by the surface of the ground (*e.g.*, A32). Therefore, they revealed stronger preferences for the tactile interface than for the audio interface (Q5 and Q6).

7.3.2 Disadvantages: Vibration Alerts. Some participants expressed some concern about recognizing the vibration alerts. In the controlled environment, all participants successfully avoided collisions using the vibration alerts. However, in the real-world environment, two participants sometimes could not recognize the vibration alerts and had imminent risks of collisions. In the controlled environment, the floor was carpeted, and the vibration alerts were clear. However, in the real-world environment, the floor was tiled with a rough surface, and the vibration alerts were mixed with the vibration of the suitcase. Eight participants commented that the effectiveness of the vibration alerts was affected by the floor texture (*e.g.*, A28 and A29). These results indicate that the vibration alerts are affected by the type of floor surface. The participants provided significantly lower scores for the effectiveness of the vibration alerts in the real-world environments than in the controlled environments (Q2).

The one possible solution to overcome this limitation is to attach vibration motors to a user's body, such as on a wrist or fingers. All participants mentioned that the directional lever was always useful and effective in both environments (*e.g.*, A32). This may suggest that the directional lever in a shape-changing interface was effective for the guiding system and that this interface is better than vibration signals for indicating alerts.

Participants were asked to adjust their walking speed on the basis of the pulse duration of the vibration, but it was hard for some participants (A27). Another possible solution is to equip brakes on the wheels of the suitcase and to control the walking speed using the physical feedback from the suitcase handle.

7.4 Form-factor of the System

We designed the system to be attached to standard luggage like a rolling suitcase. Rolling suitcases can be seamlessly used in public spaces, are well designed to walk with when holding the device, and can have all necessary sensors and tactile devices mounted on them, and enable images to be captured without significant motion-induced blur from the mounted camera (see also 3.3 Attachment Design above). Eight out of 14 participants mentioned that the suitcase-shaped system might be too heavy for daily usage (A13–A15). This suggests that the device will be accepted when they use a suitcase (or any other similar luggage) for other purposes, and then attach the system as assistive technology. At this moment, our solution is comprised of a depth camera and a laptop, which increase the weight and reduce the available space (for luggage) in the suitcase. This situation usually happens when a new assistive technology is developed [11, 53]. We expect that the size and weight of both the sensors and processors will be decreased as the device and communication technologies are systematically improved, enabling cloud-based computational power in the near future.

Another result related to the form is the possibility of mobile devices with total functionality. The directional lever was well accepted by all participants, and some commented that they would want to use the device on a daily basis if it were made the size of a mobile device (A9 and A10). We have to overcome technical challenges to enable such a form, but our results suggest a high possibility of utilizing mobile shape-changing devices.

7.5 Integrating a Guiding System to O&M Training Methods

Some participants commented that the experiments were their first time they were able to avoid pedestrians by following the instructions from a system (A9 and A10). Also, while all participants could learn how to use the system after a short training session (10 – 20 minutes), three of them commented that it took time to get used to the directional lever (A33). We asked participants to hold the suitcase handle with one hand and the white cane with the other. One participant (P6) commented that she want to keep her other hand free (A14). The current orientation and mobility (O&M) method is based on a white cane as the primary tool, and it uses all possible senses to understand the situations. Skill is required to recognize non-visual landmarks and to navigate safely in public spaces. Therefore, all blind users are strongly recommended to take O&M training [76] when they start walking independently. The use of systems for O&M is an uncharted territory for not only an individual blind user but also the entire community who supports O&M for the blind. In the near future, we should share the results and our experience with the community and discuss how to build new O&M methodologies by fully utilizing both traditional navigation aids and new technologies, including the system we introduced in this study.

7.6 Autonomous Guiding Systems

The off-path mode requires a guiding system to navigate users accurately. A future solution for such navigation needs can be autonomous guiding robots [5, 6, 23, 26, 39, 71, 73]. Our non-autonomous guiding system has the advantage of allowing users to control their speed voluntarily even during an off-path situation. The directional lever successfully achieved sufficient accuracy for the off-path navigation. We believe that our guiding interface and autonomous guiding robots will complement each other to broadly satisfy blind users' needs, such as a variety of mobility skills, familiarity with a target public space, the density of crowds, and the preferences of users.

7.7 Other Guiding Situations in Public Spaces

We focused on two typical situations for this study: walking and standing pedestrians. No comprehensive list for such situations has been reported in previous studies to the best of our knowledge, but imagining other situations is not difficult. For example, a blind user may have difficulty in following a queue to get on a train car at a station, walking together with sighted surrounding people in the same direction, and walking through an extremely crowded public space. Such situations are beyond the scope of this study, and further research is required to cover a comprehensive set of situations.

7.8 Comparing with Traditional Navigation Aids

This study was not designed to compare the proposed system with traditional navigation aids such as a cane or guide dog, because traditional methods are very challenging in public spaces. Previous studies reported that blind pedestrians using only traditional methods had difficulty avoiding collisions with nearby pedestrians [1, 16, 34, 51, 74]. In fact, 13 out of 14 participants in our study mentioned that they had collided with other pedestrians while walking. On the other hand, we believe that it would be informative for researchers and developers to understand how blind pedestrians behave when using traditional methods in public spaces as the baseline. Therefore, we plan to measure, evaluate, and create a model of such behaviors and compare traditional methods with other new navigation methods, including our system.

8 CONCLUSION

We presented a guiding system equipped on a rolling suitcase to help blind people walk in public spaces seamlessly with nearby pedestrians. The system recognizes and predicts surrounding people's behavior and predicts the risks of collisions. The system then recommends the user to adjust his or her walking speed (the on-path mode) or to take an alternative path around pedestrians (the off-path mode). We implemented tactile and audio interfaces and conducted a user study with 14 blind participants. The results revealed that blind users could successfully avoid pedestrians using both interfaces; the tactile interface for the off-path mode guided blind participants significantly faster than the audio interface could; and the sound-based audio interface was easier for recognizing alerts than the vibration-based tactile interface. Overall, blind participants believed that a tactile interface could be effective because it did not block ambient sound. In future work, we will further research new tactile interfaces to eliminate the weakness of vibration alerts by focusing on shape-changing interfaces. We also plan to collaborate with orientation and mobility (O&M) communities for building new O&M methodologies with technologies by sharing our results and experiences.

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