# BlindPilot: A Robotic Local Navigation System that Leads Blind People to a Landmark Object

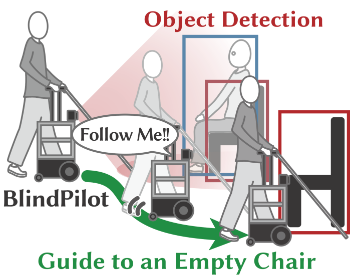


**Figure 1:** We present a local navigation robot, BlindPilot, which directly leads blind users to an empty chair.

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## Abstract
Blind people face various local navigation challenges in their daily lives such as identifying empty seats in crowded stations, navigating toward a seat, and stopping and sitting at the correct spot. Although voice navigation is a commonly used solution, it requires users to carefully follow frequent navigational sounds over short distances. Therefore, we presented an assistive robot, BlindPilot, which guides blind users to landmark objects using an intuitive handle. BlindPilot employs an RGB-D camera to detect the positions of target objects and uses LiDAR to build a 2D map of the surrounding area. On the basis of the sensing results, BlindPilot then generates a path to the object and guides the user safely. To evaluate our system, we also implemented a sound-based navigation system as a baseline system, and asked six blind participants to approach an empty chair using the two systems. We observed that BlindPilot enabled users to approach a chair faster with a greater feeling of security and less effort compared to the baseline system.

## Author Keywords
Visual impairments; local navigation; robotic system.

## CCS Concepts
•**Human-centered computing** → **Accessibility technologies;**

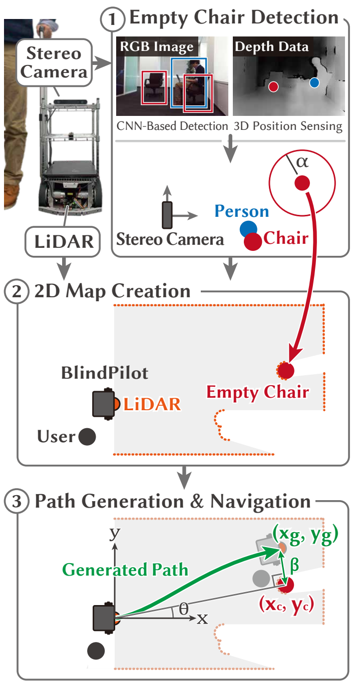


**Figure 2:** Overview of BlindPilot. (1) The system detects the positions of chairs and people using a stereo camera. Then, it judges whether each chair is empty by considering the estimated positions. (2) It then builds a 2D map of the surrounding area using SLAM and maps the positions of the empty chairs. Finally, (3) it generates a path toward the goal position $(x_g, y_g)$ next to the chair $(x_c, y_c)$ and leads the blind user by moving along the selected path.

## Introduction

Independent travel is a major challenge for blind people as they sometimes need to interact with a landmark object such as a door when entering a room, a button when using an elevator, and a chair when arriving in a lounge. Interactions with such objects require significant effort and time for blind people because of their lack of visual perception.

Several local navigation systems have been proposed in previous studies to detect landmark objects such as doors and chairs and provide information concerning the detected objects (*e.g.*, direction and distance) via sound and speech [9, 25] or tactile [28] feedback to blind users. These systems enable users to approach a detected object while correcting their direction; however, it is difficult for blind people to maintain a straight trajectory in open spaces [14, 29]. Therefore, such systems require blind users to repeatedly adjust their orientation for precise navigation.

To resolve this limitation, robotic systems have been proposed in the domain of global navigation systems [4, 5, 17, 26, 13] and obstacle avoidance systems [10, 26, 27, 13]. Users can walk by following the movement of the autonomous robots in the same manner as guide dogs. Inspired by these robot-based systems, we propose a local navigation robot, *BlindPilot*, which can lead blind users directly to landmark objects (Figure 1). By only following the movement of BlindPilot, blind users can reach a target object faster with less effort compared to previous local navigation systems providing sound/speech feedback. In this study, we focus on a scenario in which BlindPilot detects an empty chair and guides a blind user to that chair.

BlindPilot detects the 2D positions of chairs and people by using an RGB-D camera and a convolutional neural network (CNN)-based generic object detector [24]. Then, the system determines whether each chair is empty by considering the estimated 2D positions of the chairs and people. The system then builds a 2D map of the surrounding area using LiDAR and simultaneous localization and mapping (SLAM). After mapping the positions of the empty chairs on the 2D map, the system generates a path to an empty chair and moves along the generated path.

To evaluate the effectiveness of BlindPilot in approaching landmark objects, we performed a user study with six blind participants. As a baseline system, we implemented a sound feedback system on the basis of a previous study [9]. Then, we requested the blind participants to approach a chair using either the proposed system or the baseline system. We observed that BlindPilot enabled users to approach an empty chair significantly faster compared to the baseline system with sound feedback. Moreover, on the basis of the qualitative feedback from the blind participants, we confirmed that the robotic local navigation system could navigate blind users with a greater feeling of security and less effort. On the basis of our findings, we discuss certain future directions for research to realize a more flexible and comfortable navigation robot for blind users.

## Related Work

*Global Navigation Systems*

Various global navigation systems have been proposed (*i.e.*, turn-by-turn navigation systems) [1, 3, 4, 6, 8, 11, 18, 20, 21, 23] that can localize a blind user and provide the shortest or safest route to a destination. However, these systems do not completely support local navigation in which blind users need to interact with certain objects. For example, although a blind person may arrive in a lounge using a global navigation system, they then need to identify a chair using their hands or a white cane. To overcome this limitation, it is important to support both global navigation and local navigation.

*Local Navigation Systems*
White canes are the most commonly used tools by blind people to identify landmark objects. While canes are useful, their sensing range is limited by their length (approximately 1 m) [16]. To augment the sensing range of blind users, several local navigation systems have been proposed in prior studies. These systems can detect landmark objects (*e.g.*, doors [9] and chairs [28, 25]) using an optical head-mounted display [9] or a stereo camera [28] and provide information to navigate toward the detected objects (*e.g.*, direction and distance) via audio [9, 25] or tactile [28] feedback to users. Although blind users can approach a certain object while correcting their direction on the basis of this feedback, they need to finely and repeatedly adjust their orientation. Therefore, we propose a robotic local navigation system that directly leads blind users to a landmark object.

*Robotic Navigation Systems for the Blind*
To realize a global navigation system, in recent studies, robotic systems have been proposed that can guide blind users along a route toward a destination [4, 5, 17, 26, 13]. Azenkot *et al.* discussed requirements for global navigation robots with several blind participants and designers [5]. Recently, Soto *et al.* proposed a quadcopter-based global navigation system [4] and conducted a user study showing that blind users can reach a destination faster when following the movement of leashed quadcopters compared to audio-based navigation.

To support obstacle avoidance, robotic systems have been proposed that can detect static obstacles and automatically avoid detected objects [10, 26, 27, 13] in the same manner as guide dogs. Users can perceive and follow changes in the direction of such a system. Inspired by these robot-based global navigation or obstacle avoidance systems, we propose a navigation robot for the blind that supports local navigation tasks by generating a fast and safe path using landmark object detection.

## Proposed System
As shown in Figure 2, BlindPilot guides blind users in three steps: 1) empty chair detection, 2) 2D map creation, and 3) path generation and navigation. All processes are performed on a laptop computer[1] attached to a mobile robot.

*Step 1: Empty Chair Detection*
BlindPilot is equipped with a ZED™stereo camera[2] to capture RGB images and collect depth data. BlindPilot uses YOLOv3 [24] to detect chairs and people using the RGB images. We used the central areas of the detected bounding boxes to obtain the 2D positions of the detected objects in the camera coordinate system [15]. The system determines that a detected chair is empty if there are no existing people within a distance $\alpha$ from the chair position (Figure 2(1)). We set the parameter value $\alpha = 1$ m for all of our studies.

*Step 2: 2D Map Creation*
The system builds a 2D map of the surrounding area by using ROS gmapping [12], which can create a floor plan and the pose trajectory of a mobile robot using laser-based SLAM. We used a commercially available mobile robot[3] and attached a LiDAR unit[4] to the robot (Figure 2). After creating the 2D map, the system maps the position of the empty chair estimated in Step 1.

*Step 3: Path Generation and Navigation*
The system generates a path next to the target chair and automatically leads the blind user by following the generated route. This navigation system is built on the ROS

[1] CPU: Intel®Core™i7-8750H and GPU: NVIDIA®GeForce®GTX 1080
[2] https://www.stereolabs.com/zed/
[3] https://www.vstone.co.jp/english/index.html
[4] https://www.hokuyo-aut.jp/search/single.php?serial=166

navigation stack [19], which comprises a path planner, a localization system, and a mobile robot controller. We set the max velocity of the robot to $1.2\,\mathrm{m\,s^{-1}}$. The path planner can generate a path that avoids static obstacles.

To enable users to easily sit in chairs, the system sets the goal position to the left of the target chair. More formally, let $(x_c, y_c)$ and $\theta$ be the position and direction of a detected empty chair, respectively, as illustrated in Figure 2(3), then the system computes the goal position $(x_g, y_g)$ (Equation 1), which the system publishes to the ROS navigation stack.

$$\begin{cases} x_g = x_c - \beta sin\theta \\ y_g = y_c + \beta cos\theta \end{cases} \qquad (1)$$

Let $\beta$ be the distance between the target chair and the goal position. We set the parameter value $\beta = 0.7$m for all of our studies. When BlindPilot starts or ends the navigation, the system outputs an audio message such as *“Starting the navigation”* or *“Arrived at the destination.”*

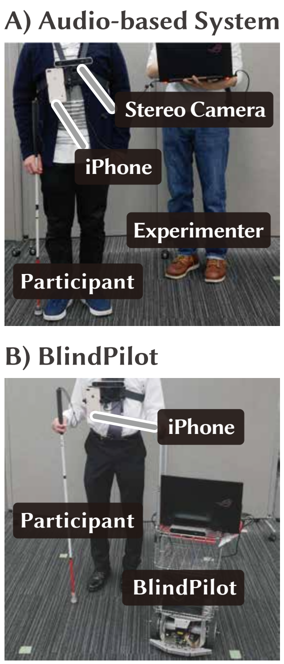


**Figure 3:** In our user study, we compared two systems: (A) an audio-based system and (B) a robot-based system (BlindPilot).

## User Evaluation

We performed a user study in which six participants (male: 4, age: $24.5 \pm 4.2$ (mean and SD)) approached an empty chair. In this study, we compared BlindPilot to an existing audio-based local navigation system.

*Baseline System*
We implemented an audio-based system on the basis of a previous study [9], in which Google Glass was used to estimate the position of a door and text-to-speech feedback was provided such as *“right”*, *“left”*, and *“straight X m”* every $1$ s. In our study, we mounted a ZED camera, rather than Google Glass, on the participants’ chests and detected the chair. While participants were using this system, an experimenter followed them to carry the laptop (Figure 3(A)).

*Tasks and Procedure*
The primary focus of our study was to investigate which interface (robot-based navigation or audio-based navigation) is more effective and comfortable for blind users. Accordingly, we placed a chair in a square space ($6$ m $\times$ $11$ m) and asked participants to approach the chair. We prepared three types of routes to the target chair: Front (the target was straight ahead with respect to the start), Right ($20°$ to the right), and Left ($20°$ to the left). For all routes, the distance between the start position and each target was 6 m.

After obtaining informed consent from the participants, we gave them a short training session until they were familiar with the systems. Then, they were requested to approach the chair three times using one of the systems (the proposed or baseline system) while the position of the chair was changed (Front, Right, and Left). Next, they approached the chair three times using the other system. For each participant, the order of the three target positions and two systems was randomized. We mounted an Apple®iPhone®$8$ Plus smartphone on the participants (Figure 3) to obtain their trajectories of them by using ARKit.

*Metrics*
**Task Completion Time:** We measured the times that elapsed before the participants sat on the chair (*i.e.*, the task completion time). We compared the task completion times of two systems on the basis of a 95% confidence interval and the Wilcoxon signed-rank test with 5% levels of significance.

**Post-Interview:** After completing all the tasks, we asked the participants to fill out a questionnaire (the statements are shown in Figure 4). We designed the questions on the basis of the Quebec User Evaluation of Satisfaction with Assistive Technology (QUEST 2.0) [7]. They answered these questions in the form of a seven-point scale ranging from 1: more inclined toward the baseline system, 4: neutral to 7: more inclined toward BlindPilot. Finally, we conducted an interview session for about 15 minutes to receive qualitative feedback.

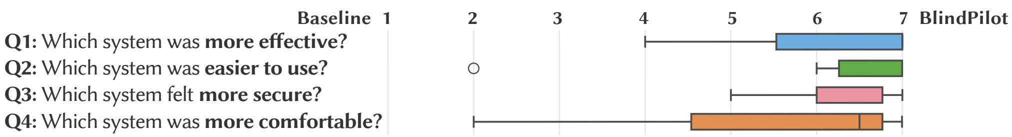


**Figure 4:** Likert items (1: the baseline system to 7: BlindPilot) and a summary of the answers.

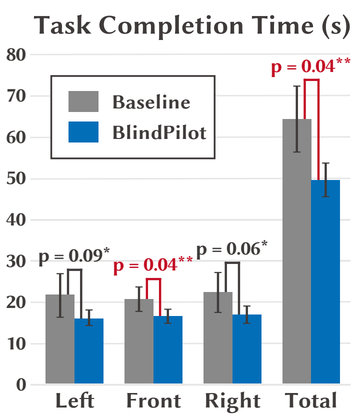


**Figure 5:** Task completion time: The bars show the 95 % confidence intervals. $p$: $p$-value of the Wilcoxon signed-rank test ($*$ and $**$ indicate the significance confirmed at the 0.1 and 0.05 levels, respectively).

## Results

*Task Completion Time*

Figure 5 reports the task completion time. Our statistical analyses confirmed the statistical significance and the superiority of BlindPilot over the baseline system for all tasks. Figure 6 shows certain examples of trajectories of participants. While the blind participants walked in a zigzag line to adjust their orientation when they were using the audio-based system (Figure 6(A)), they could approach the chair smoothly using BlindPilot (Figure 6(B)). Furthermore, when the participants used the sound system, they adjusted their orientation $2.9 \pm 1.3$ times (mean and SD) during each task.

*Post-Interview*

Figure 4 reports the results of our questionnaire. We confirmed that BlindPilot satisfied all but one participant (P1).

Five of the participants who valued BlindPilot mentioned that the advantage of BlindPilot was that they could walk with a greater feeling of security: **A1:** *"Because the robot led the way, I did not have to worry about collisions with obstacles."* (P2–P4) and **A2:** *"I felt secure because walking with the robot was similar to the feeling of walking with a person."* (P5). Although P1 liked the baseline system, P1 also acknowledged that BlindPilot provided a feeling of security: **A3** *"I could approach a chair with a feeling of security because the robot directly guided me."*

Participants also reported that they could effortlessly approach the chair by following the movement of BlindPilot: **A4:** *"Because the robot automatically approached the chair, I could reach the chair easily by following the movement of the robot."* (P1–P3, and P6); and **A5:** *"When I used the robot system, I could approach the chair more smoothly compared to the sound system."* (P1). On the other hand, they commented that following the frequent navigational sounds of an audio-based system was difficult: **A7:** *"It was difficult for me to walk straight. So, when I used the sound system, I had to change my orientation repeatedly."* (P2, P4, and P6); and **A9:** *"The sound system required that I repeatedly adjust my orientation. This may increase the risk of collision with other pedestrians or obstacles."* (P1).

We obtained two types of negative opinions with respect to BlindPilot as follows: **A10** *"I want to know the position of the destination before the robot starts its navigation. I also want to know the movement of the robot. For example, the robot could turn right after saying "Turn right."* (P1 and P3) and **A11** *"The robot system does not change speed when approaching the goal."* (P1 and P6).

The participants said they wanted to be guided to an empty chair **A12:** when they are in a train (P1–P4, and P6), food court (P2 and P3), or non-territorial office (P3 and P5). Furthermore, participants commented that they want to use a local navigation system **A13:** when they look for an entrance to a shop (P1–P5) or a train door (P2 and P4).

## Discussion

*Advantages of BlindPilot*

Our quantitative evaluation revealed that, **with BlindPilot, blind participants were able to access an empty chair faster** compared to when using the audio-based navigation system. Moreover, we confirmed that the majority of partic-

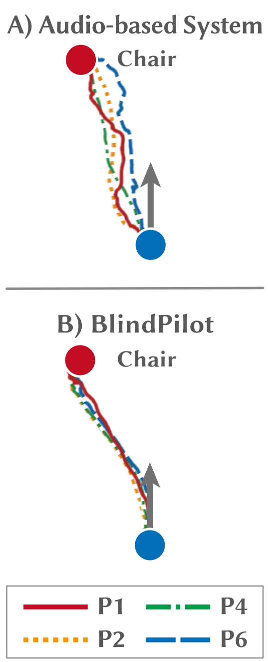


**Figure 6:** Trajectories of the blind participants approaching the chair on their left while using (A) BlindPilot or (B) the baseline system.

ipants (five out of six) were satisfied with BlindPilot according to our questionnaire (Figure 4). The feedback showed that **BlindPilot could guide blind users with a greater feeling of security and less effort** (A1–A6) and following the frequent navigational sounds of the audio-based system was difficult (A7–A9). These results indicate that a local navigation robot is a promising approach to enable easy local navigation for blind people with confidence (a feeling of security). Furthermore, the participants reported that they wanted to use the robotic system to identify empty chairs, entrances, and doors in public spaces (A12–A14). It is necessary to evaluate multiple factors in practical public environments such as occlusion of the landmark objects by crowds and non-smooth movements that may be necessary to avoid obstacles.

*Limitations and Possible Extensions*

A number of participants reported the need to convey more informative feedback from the robot to the blind users. They suggested to provide information about the position of the destination and the movement of the robot in advance (A10). For global voice navigation systems, the importance of an explanation for a current location is well known [22]. Furthermore, in autonomous robotic navigation, it is important to guide blind users while describing the next movement of the robot rather than guiding blind users in silence. Local navigation is more time critical compared to global navigation; therefore, the time available for such an explanation may be limited in practical situations. The timing, interaction methods, and amount of information should be well designed through future studies.

Both P1 and P6 reported that a drawback of the BlindPilot experience was the inability of the user to control the walking speed. The current implementation does not enable the user to change speed when the robot is leading the user. This is one example of the well-known challenge of shared control [2], a situation when a user feels less independent when a robot does not accept any control even if the user is aware of better or more comfortable methods of completing the task. This result indicates that future versions of BlindPilot should provide shared control at least for speed control. The most commonly used solution is to enable a shift of control authority in real time during movement. We expect that the robot will need to provide shared control for many other aspects, such as orientation, route, and landmark object selection, to improve the user experience. The timing and interaction methods to improve control flexibility require further studies.

## Conclusion

We proposed a local navigation robot, BlindPilot, which directly guides blind users toward an empty chair. The system detects the position of an empty chair using a CNN-based object detector and stereo image sensing. BlindPilot then generates a path to the chair and moves along the generated path. We evaluated the effectiveness of BlindPilot for six blind people. The results showed that BlindPilot guides blind users significantly faster than a sound-based local navigation system. Furthermore, our qualitative analysis showed that BlindPilot could guide blind users with a feeling of security and less effort as well as limitations such as explainability, and walking speed control. In future, we plan to implement and study a robotic system that can provide informative feedback and shared control toward our ultimate goal to create practical solutions for blind people to travel independently.

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