SlopeNav: A Realtime Wearable Blind Ski Assistance System with Adaptive Path Planning for Simulated Environments

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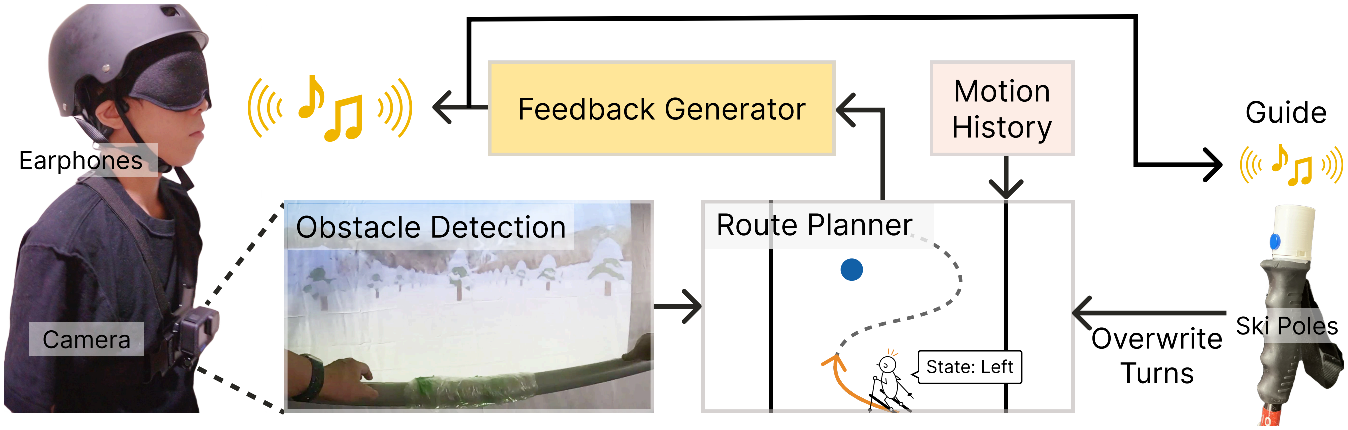

Figure 1: SlopeNav consists of a chest-mounted camera and earphones. As a skier descends a slope, the camera captures real-time video, which the system then analyzes using an object detection algorithm. When an obstacle is detected, auditory feedback is delivered to the skier through the earphones at appropriate timings, guiding them safely in the correct direction.

Abstract

Skiing is a visually demanding sport that presents significant challenges for individuals who are blind. In this study, we propose a prototype system called **SlopeNav**, designed to assist blind skiers in safely and independently navigating slopes. The system combines a chest-mounted camera with auditory feedback to provide real-time obstacle detection and path guidance. It dynamically identifies safe routes based on course conditions and the skier's skill level, offering continuous turn guidance during navigation. We conducted evaluation experiments involving four blind skiers, four guides, and four sighted participants who were blindfolded. The results demonstrated that, in a simulator environment, the system enables obstacle avoidance with safety comparable to that provided by human guides. These findings indicate that continuous turn guidance and skill-adaptive route planning are effective for obstacle avoidance in skiing.

CCS Concepts

• **Human-centered computing → Accessibility systems and tools**.

Keywords

blind skiing, visual impairment, ski simulator, sonification, winter sports, ski safety

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1 Introduction

Engaging with the world often relies heavily on our visual sense. For blind individuals, the absence of vision makes many everyday activities significantly more challenging. This challenge becomes particularly pronounced in sports and physical activities, where coordination between vision and body movement plays a critical role [4]. Despite these difficulties, blind individuals have overcome numerous barriers to actively participate in a wide range of sports, including cycling, soccer, and even shooting [24]. However, blind individuals face more limited access to sports compared to sighted individuals [40]. Within this landscape, skiing stands out as one of the exhilarating yet complex sports, with its unpredictable terrains and rapidly changing conditions.

Usually, blind individuals have relied on sighted guides for sports like marathons, swimming, and skiing. These guides provide real-time verbal instructions to help blind individuals avoid obstacles and maintain their pace [42]. However, the availability of skilled guides is insufficient to meet the demand among the blind population. Recent studies have begun exploring technology-assisted approaches to enhance real-time guidance [1, 9]. Furthermore, advancements in indoor skiing simulators have enabled training experiences without the need for human guides [27]. While these simulators offer safe and controlled environments, they cannot fully replicate the complexities of real-world skiing and still require human guidance in many cases.

To address these challenges, we aim to bridge the gap between simulation and real-world environments and develop a system that allows blind skiers to practice independently of skilled guides. Recognizing the significant gap between simulated and real-world conditions, we outline a three-step pathway to achieve our goal. In Step 1, we enable obstacle avoidance in a simulated environment that mimics real skiing conditions. In Step 2, we transition to real-world skiing, where the system semi-autonomously guides blind skiers with assistance from sighted guides. Finally, in Step 3, the system independently guides the skier, enabling them to enjoy skiing freely alongside their guide.

This paper introduces a prototype system, **SlopeNav** (Figure 1), which offers real-time audio guidance for blind skiers by detecting obstacles in a simulated environment using a chest-mounted camera. SlopeNav successfully addresses Step 1 and establishes the groundwork for Step 2. To ensure both safety and an optimal skiing experience, we conducted preliminary experiments and developed SlopeNav based on the results. These experiments highlighted the importance of continuous feedback, skill-adapted route exploration, and collaboration features with guides.

To evaluate SlopeNav, we conducted a study involving four experienced blind skiers and their sighted guides. We compared the proposed system with traditional guide-based methods and conducted comprehensive interviews with both skiers and guides to qualitatively assess the system. The results demonstrated that the system successfully enabled obstacle avoidance in a simulated environment, and all participants provided positive feedback on its potential for future development.

The primary contributions of our work lie in:

- **Pioneering Prototype, SlopeNav:** A wearable, user-friendly chest-mounted camera system, co-designed with blind individuals to address the specific requirements of blind skiing.
- **Path Planning & Auditory feedback:** A method for designing a safe path via vision-based obstacle detection coupled with distinct auditory feedback.
- **User Study & Insights:** A hands-on comparison of our auditory feedback systems, offering insights into user experiences and highlighting areas ripe for enhancement.

2 Related Work

2.1 Sports Assistance for People with Visual Impairment

The world of sports continues to evolve to accommodate a more diverse range of audiences and players. Various approaches have proposed systems to support sports activities for blind individuals. Exergames customized for blind individuals stand out as a testament to this progress [28, 29]. Adaptive systems, custom-made for activities that span yoga [38], badminton [18, 41], climbing [15, 39], running [37], hiking [22], and kayaking [2, 19], have broken barriers, allowing blind enthusiasts to indulge without being attached to constant assistance.

With respect to skiing, tactile feedback systems have been developed to connect guides and blind skiers, providing assistance in navigating slopes. Aggravi *et al.* [1] introduced a system that uses ski poles with buttons to provide commands and communicate turning directions through haptic feedback. Similarly, Haladjian *et al.* [9] support bidirectional communication between guides and blind skiers by integrating haptic feedback and motion detection. Nonetheless, our research is focused on an ambitious goal: paving the way for individuals who are blind to enjoy skiing independently, without relying on a guide.

2.2 Auditory Navigation Aids

To enable blind individuals to engage in sports without the support of sighted guides, it is essential to convey the necessary information for the activity using tactile and auditory feedback. Rector *et al.* [37] investigated whether auditory or tactile feedback is more effective for blind individuals running on a track. The study found no significant difference between the two types of feedback, but noted that perceiving vibrations becomes challenging when users are holding objects such as canes or guide dogs. Sound has been widely utilized in various applications, ranging from text-to-speech solutions [6, 17, 21] to advanced sonification techniques [20, 23, 35]. These systems effectively convey spatial information, such as distance and size [8, 12, 36, 46]. Moreover, innovations in stereo and 3D audio have further enhanced the effectiveness of directional guidance [35, 43].

In the specific context of blind skiing, turn guidance systems such as Advance Turn Sound (ATS) and Continuous Error Sound (CES) have been explored [27]. ATS conveys turn timing, direction, depth and length using pitch and duration, while CES represents deviations from an ideal ski course through changes in pitch and volume. ATS effectively communicates turn-related information but is based on fixed durations, limiting its flexibility for undefined routes. CES, on the other hand, can be challenging due to abrupt and noisy transitions. To address these issues, this study proposes a feedback method that builds on ATS and CES by making ATS temporally continuous.

2.3 Ski Training Systems with Multi-Modal Feedback

Skiing presents unique challenges. Prior research has explored various methods to improve skiers' posture, including auditory feedback [5, 11], visual information [25, 26, 33, 44, 45], and tactile feedback [13]. Additionally, systems have been developed to enhance safety and information sharing in ski resorts [7, 14, 31, 32]. For instance, Niforatos *et al.* [31] proposed a LiDAR-equipped helmet to improve situational awareness and safety in skiing environments. However, these studies primarily focus on sighted individuals, leaving the needs of blind skiers largely unaddressed.

For blind individuals, existing research has centered on auditory feedback in ski simulators [27] and the development of exercise games [30]. However, the skiing paths in these studies are fixed, leaving a significant gap compared to real-world skiing. To address this gap, our goal is to bridge the gap between ski simulators and outdoor skiing, enabling blind individuals to independently train and prepare for skiing.

3 Preliminary Experiment

Previous studies have focused on auditory feedback in predetermined courses [27]. However, in real ski environments, turns are more flexible, and terrain and obstacles change frequently. In this study, we build upon previous findings [27] by improving feedback methods and integrating them with a vision-based obstacle detection algorithm. To gain deeper insights into the challenges and expectations of navigation in actual skiing, we conducted preliminary experiments with four blind skiers. Based on the feedback obtained, we identified the requirements for a skiing assistance system for blind individuals, with a future goal of enabling obstacle avoidance in collaboration with guides during real skiing.

3.1 Obstacle Avoidance Using Audio Feedback

Four blind skiers (**PP1-PP4**) and four guides (**PG1-PG4**) participated in an experiment to evaluate auditory-based obstacle avoidance and were interviewed. The simulation consisted of a 12 m wide straight path, with 10 obstacles placed at random positions along the path. The prototype system guided the skier using earphone sounds emitted based on rules on the position of obstacles and the skier. Based on previous research, the system employed an auditory feedback method called ATS [27], which uses sinusoidal sound waves to convey the magnitude and depth of turns through the direction, intensity, and pitch of the sound.

The simulation environment was the same as described in Section 4.6. The skiers wore earphones and a camera and performed turns according to the given instructions. Each participant practiced using the system in the simulator before experiencing both human-guided and system-guided navigation. After the session, interviews were conducted with both the guides and blind skiers to identify the functionalities and feedback methods needed for real skiing scenarios.

3.1.1 *Challenges in Feedback from the Prototype.*

Participants who experienced system feedback often reported anxiety during periods of silence: **PP1**: "When there is no sound for a long time, I feel anxious because I can't tell how I'm moving or whether the system is working.", and **PG1**: "When guiding a skier, I extend the end of instructions to avoid any breaks in sound."

Experiment results showed that skiing skills and turn timing vary among individuals. Preliminary tests revealed discrepancies between the system's instructions and skiers' perceived paths, caused by factors like uneven turn widths and reaction speeds. Human guides adapt their instructions based on the skier's abilities: **PG2**: "We discuss and observe the skier's performance in advance to understand their habits and skills, then provide customized turn instructions."

3.1.2 *Challenges in Collaboration Between Guides and the System.*

System-guided and human-guided skiing each have their strengths. In early trials at real ski resorts, a semi-automated guide system combining human guidance emerged as a crucial component. This integration could also enhance safety: **PP3**: "Using both the guide and the system helps verify the accuracy of the instructions." However, integrating the two poses challenges, highlighting the need for a dedicated guide system: **PG1**: "I feel uneasy watching because I don't know what instructions the system is giving."

3.2 Design Requirements Distillation

Based on the preliminary experiment, we outline the following design requirements for a guidance system that enables safe skiing while avoiding obstacles.

- ($D1$): **Proactive Obstacle Avoidance:** Skiers, navigating at high speeds, must account for both obstacle locations and the course layout to execute safe turns. The proximity of obstacles can lead to overcautious behavior, disrupting their natural turning mechanics. Clear and direct guidance is preferred, particularly on narrow courses with numerous obstacles.
- ($D2$): **Continuous Feedback Mechanism:** Skiers express greater confidence when feedback is provided continuously, enabling sustained awareness of their current state.
- ($D3$): **Route Design Adapted to Individual Skill Levels:** The response speed and turn shapes in reaction to feedback vary depending on skiing skill levels. To construct safe routes, it is essential to adjust the timing of feedback and the size of turns.
- ($D4$): **Feedback in Collaboration with Guides** Real-world skiing environments feature diverse terrains and obstacles, where system decisions may sometimes pose risks. To ensure safe skiing while utilizing system support, it is desirable to have a mechanism that allows guides to intervene in the system.

Based on the design requirements, a feedback system was developed to guide skiers safely. The system provides feedback on the timing, direction, and magnitude of turns using stereo sound (**$D1$**). The feedback operates continuously until the turn is completed (**$D2$**). Additionally, avoidance routes are constructed according to the skier's skill level. Turn trajectories in response to feedback are recorded and used to adjust the route (**$D3$**). Furthermore, a guide input/output device was designed, enabling guides to override the system's instructions. This device utilizes earphones and buttons mounted on ski poles for intuitive operation (***D*4**).

4 Implementation

Based on the extracted design requirements, we implemented a system that enables blind individuals to avoid obstacles and ski safely. The system consists of the following components: obstacle detection, construction of obstacle avoidance routes, auditory feedback, and integration with a guide. This section provides a detailed explanation of each component.

4.1 Wayfinding and Obstacle Avoidance

The system constructs a map from detected obstacle positions and plans an avoidance course. Since skiing alternates between left and right turns, the route planning prioritizes turns and uses straight movement only to avoid danger. When obstacles are densely packed, the skier slows down and moves straight. To reflect this, the skier's state $S \in \{left, right, straight\}$ is determined by the most recent turn, and consecutive turns in the same direction are prohibited.

The system converts the map to Frenet coordinates using the course centerline as a reference. It samples $n \times m$ points along the path and evaluates each using a cost function, interpolating between points with cubic functions based on past movement data. The total cost C_{total} for each sample point is expressed as:

$$C_{total} = C_{smooth} + C_{obj} + C_{slope}. \tag{1}$$

Path Smoothness. Smoothness is calculated based on the rate of change in the direction of the path $f(s)$. It is defined as:

$$C_{smooth} = w_1 \int \left(f'(s)\right)^2 ds. \tag{2}$$

Obstacle Avoidance. The collision risk near an obstacle is evaluated using the following equation, where d is the distance to the obstacle, d_n is the safe distance, and d_c is the collision threshold:

$$C_{\mathrm{obj}}(d) = \begin{cases} 0, & d > d_n \\ C_{nudge}(d_n - d), & d_c \leq d \leq d_n \\ C_{collision}, & d < d_c \end{cases} \tag{3}$$

Course Alignment. To maintain alignment with the course while adjusting the turn width, the system evaluates the distance from the centerline of the course $g(s)$. This is expressed as:

$$C_{slope} = w_2 \int \left(f(s) - g(s)\right)^2 ds. \tag{4}$$

The system optimizes the path with dynamic programming, selecting the route that minimizes the total cost. At each point, the set of possible actions A was explored, and the skier's state S, and the cost was updated at the resulting point after each action. The transition points after applying the action set to the point ((0,0),Right) are shown in Figure 2b. In simulator experiments, it sampled 12×20 points and planned routes up to 20 meters ahead to balance speed and computational efficiency.

4.2 Adaptive Path Planning

Skiers differ in their skill levels, preferred turns, and reaction times to feedback. To accommodate these variations and enable adaptive route planning, we implemented a simple turn path prediction. First, the system records feedback A, the immediate preceding speed v, and the turn trajectory $\mathbf{x}$ from the start of the feedback to the next feedback. By using the feedback initiation as the reference point for data, the system can predict not only the trajectory but also the skier's reaction to the feedback.

Next, the velocity is divided into bins, and a trajectory prediction model $\hat{\mathbf{x}} = f(A, v)$ is created for each type of feedback and velocity range. In SlopeNav, it is assumed that trajectories can be expressed using cubic functions, and predictions are performed using linear regression (Figure 2a). The initial values of the prediction model are set to the average values of blind skiers recorded in advance, and the model is updated after each turn performed by the skier.

4.3 Auditory Feedback

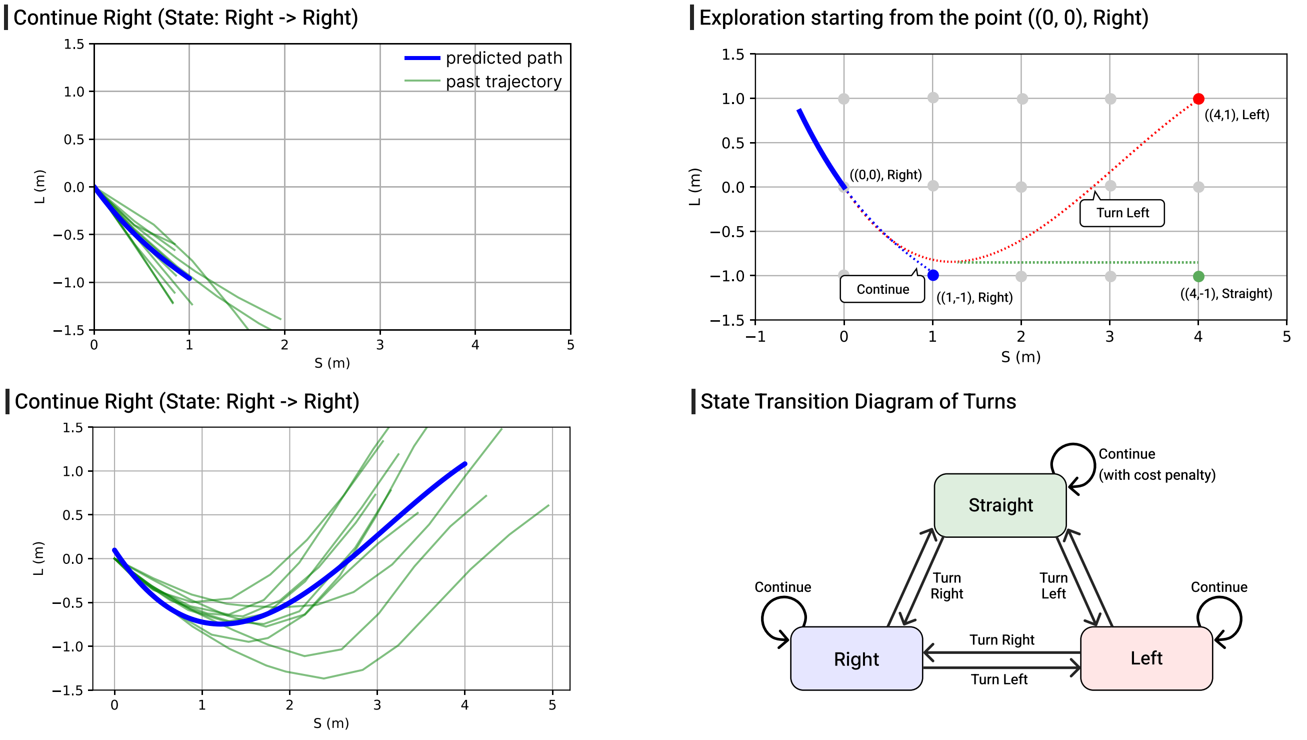
SlopeNav employs stereo auditory feedback for the left and right ears, combining direct turn instructions with indirect turn guidance based on deviations. We chose not to use haptic feedback due to the difficulty users might face in distinguishing it from the natural vibrations experienced during skiing.

4.3.1 Turn Sound. We developed a sinusoidal auditory feedback system to continuously convey turn direction, length, and timing based on ATS [27]. In ATS, the timing, depth, and width of a turn are provided in advance to guide the user's next action. However, results from a preliminary experiment indicated that continuous feedback is more desirable in realistic scenarios, such as avoiding obstacles. Therefore, SlopeNav uses sound direction changes for turn direction and timing, and pitch variations for turn width.

SlopeNav conveys turn direction and timing through sound direction changes, while turn width is communicated via continuous pitch variations. The sound direction corresponds to the next turn (e.g., right earphone for a right turn). Alternating sound directions also indicate turn timing. The pitch reflects the distance to the next turn and adjusts continuously with the skier's position. For example, when a skier turns right, feedback from the previous left turn stops, and the sound shifts to the right. Initially, the skier moves leftward due to momentum, increasing the distance from the target and raising the pitch. As the skier progresses and passes the turn apex, their movement shifts toward the target, causing the pitch to gradually decrease. The feedback remains active, continuously updating to reflect the skier's position, until the transition to the next turn is triggered. The sound frequency f is determined based on the width w to the next turn, following Equation 5 ($f_{\max} = 1500Hz$, $f_{\min} = 300Hz$).

$$f = f_{\min} 2^{w \cdot \ln\left(\frac{f_{\max}}{f_{\min}}\right) \cdot \frac{1}{\ln 2}} \tag{5}$$

4.3.2 Action Feedback Sound. We developed supplementary feedback to indicate the quality of turns and guide the skier at the start of skiing. Human guides often provide not only turn instructions but also comments on turn width and course conditions. To help skiers confidently navigate and avoid obstacles effectively, we introduced sound effects to indicate when appropriate turn widths are maintained. The system evaluates turn width for each turn and plays a sound effect when the skier's performance aligns with the system's predictions.



(a) Adjustment of routes and feedback timing based on past trajectories. Routes are generated based on recent speed for each feedback type and combined for obstacle avoidance.

(b) Transition destination after applying a strategy to the point ((0,0), Right). Based on the state transition diagram of turns, the skier can continue the right turn, go straight, or switch to a left turn.

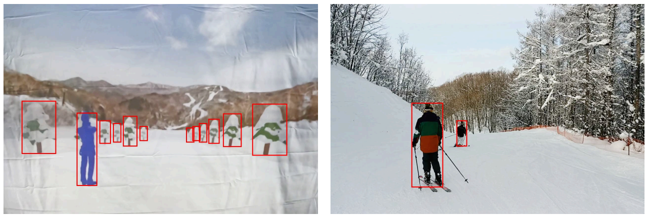
Figure 2: Route exploration process based on obstacles, past trajectories, and feedback. The system predicts the trajectory after feedback (a) and updates transition points and costs using a state transition diagram (b).

Based on the previous study, Gate-Passed Sound [27], we implemented a mechanism where maintaining correct performance continuously results in the pitch increasing sequentially to 1.2, 1.4, and 1.6. Additionally, for experiments conducted in a simulation environment, we added sounds for system start and end, as well as for collisions with obstacles.

4.4 Guide System

On actual ski slopes, a wide variety of situations may arise that the system alone cannot handle, making collaboration between the system and human guides essential. To address this, SlopeNav introduces a guide system that enables guides to monitor the system's status and intervene in the feedback, with a focus on real-world skiing scenarios.

Based on the designs from previous studies [1, 9], the guide system consists of earphones, switches attached to ski poles, and a guide system computer. The buttons on the ski poles are connected to an ESP32 device, which transmits information to the guide system via BLE (Bluetooth Low Energy). The guide system communicates in real time with the main system worn by blind skier, delivering the same feedback to the guide as that provided to the skier. If the guide deems the system's instructions unsafe, they can override them using buttons mounted on both ski poles.



(a) Real-world Indoor Image. **(b) Real-world Outdoor Image.**

Figure 3: Example images used to train the object detection model, collected from both simulated and real-world skiing environments.

4.5 Obstacles Detection

Based on the design of skiing robot systems [34], we developed a pipeline for obstacle detection. Obstacle detection was achieved using a stereo camera and YOLOv8n [16]. For depth acquisition, we utilized the OAK-D stereo camera. A total of 1,200 images captured in a simulation environment and 600 images taken on actual snow were annotated and used to train the model. Examples of the training images are shown in Figure 3. The inference time of the entire pipeline was measured at 50.5 ms. Given that the skiing speed in the simulation environment was approximately 5 m/s, we determined that this inference time was sufficient for the requirements of this study.

In the simulation environment targeted in this research, the skiing course was reproduced using a projector, which prevented depth information from being acquired. As an alternative, RGB images were captured using a GoPro HERO12 BLACK, and distance information was directly obtained from the simulation system.

4.6 Indoor Skiing Arena

Considering the inherent dangers of actual ski resorts, we establish an indoor skiing space, depicted in Figure 4. This controlled environment facilitates safe system testing and allows us to conduct a user study evaluating the proposed prototype. Our indoor skiing setup consists of two segments: a physical ski simulator and a virtual skiing game.

4.6.1 Hardware Infrastructure. To closely replicate real skiing, we use the esteemed SkyTech-Sport[1] simulator, also a training tool for the U.S. Ski Team[2]. Users wear ski boots, mount the simulator's bindings, and tilt their feet along the roll axis to simulate a parallel turn (Figure 4a). When a user tilts the ski boards, the skis slide in the tilt direction, enabling left and right movements on the simulator. For safety, we installed a handrail in front of the skier and safety nets on both sides (Figure 4b). To prevent collisions from erroneous system instructions, we placed a curtain about 1 meter before the safety nets, allowing users to physically sense the simulator's movement limits.

4.6.2 Virtual Skiing Landscape. We design a virtual skiing terrain filled with challenges, like moving figures and trees, using the Unity software (version 2022.3.35f1). VIVE trackers on the skis ensure the game mirrors the skier's real-life movements. Skiers must dodge obstacles and receive auditory feedback when passing an object, indicating success or failure in avoidance. Figure 4c shows an ultra-short throw projector displaying the user's front view in the virtual realm. The dynamic game scene moves based on the user's current position. Although participants do not see this projected scene, the virtual experience is displayed on-screen and recorded by a chest-mounted camera, simulating actual skiing.

5 User Study

To evaluate the effectiveness and user experience of our system, we conducted a comprehensive user study. The primary goal of this study was to assess skiers' performance in obstacle avoidance using the system and to collect detailed feedback on their interaction and overall experience. Specifically, we compared the proposed system with human-guided navigation to explore its potential as an alternative, highlighting its advantages and limitations. Based on the design requirements identified through preliminary experiments, we proposed the following hypotheses:

($H1$): Continuous pitch-based feedback enables skiers to trust the system's guidance and perform safe turns.
($H2$): Adaptive route designs based on individual skill levels ensure safety comparable to human guidance.

5.1 Tasks and Conditions

Blind skiers were tasked with performing turns and avoiding obstacles on the ski simulator. In this study, we compared three guidance methods: SlopeNav (System), a human guide (Guide), and a combination of both (Mix). In the Guide condition, the guide provided verbal instructions such as "right" or "left" to indicate the direction of turns. This approach replicated traditional guidance methods used in real-world skiing environments for blind skiers. In the Mix condition, the guide listened to the system's feedback and could override its instructions when necessary. By using a dedicated guidance interface, the guide could press a button attached to the skier's pole to modify or replace the system's commands. This setup simulated real-world scenarios where the guide assists with hazards that the system cannot detect or adapts to the skier's condition. For each task, a scene with 10 randomly placed obstacles was used.

5.2 Evaluation Metrics

Throughout the study, numerous performance metrics are meticulously recorded to describe each participant's performance comprehensively.

Avoidance Success Rate. This metric evaluates skiers' obstacle-dodging efficiency, expressed as the percentage of successfully avoided obstacles.

Distance Measurement. We compute the minimum distance maintained from each obstacle as it is passed, indicating the safety margin maintained by participants while navigating around obstacles.

Quantitative Questionnaire. After completing each condition, participants fill out the SUS (System Usability Scale [3]) and raw NASA-TLX [10] questionnaires to evaluate usability and subjective mental workload. In addition, after all conditions have been completed, a customized questionnaire is used to further examine the functionality and potential of auditory feedback.

Qualitative Feedback. Participants' opinions form a critical component of this study. Through interviews, their preferences and perceptions of auditory feedback are examined, providing an in-depth exploration of their subjective experiences.

5.3 Participants

We conducted the experiment with four blind skiers (Table 1) and four sighted individuals with guiding experience (Table 2). Each experiment took approximately three hours and each participant was compensated 65 USD. This experiment was conducted after obtaining the review of the Research Ethics Committee of our institution.

To evaluate the safety and adaptability of the system's route design, we conducted a supplementary experiment with four sighted participants wearing blindfolds. Due to simulator constraints, participants needed sufficient skiing skills. This approach addressed challenges in recruiting blind participants with sufficient proficiency. However, results from blindfolded sighted participants were analyzed separately, as they do not fully reflect the experiences of blind individuals.

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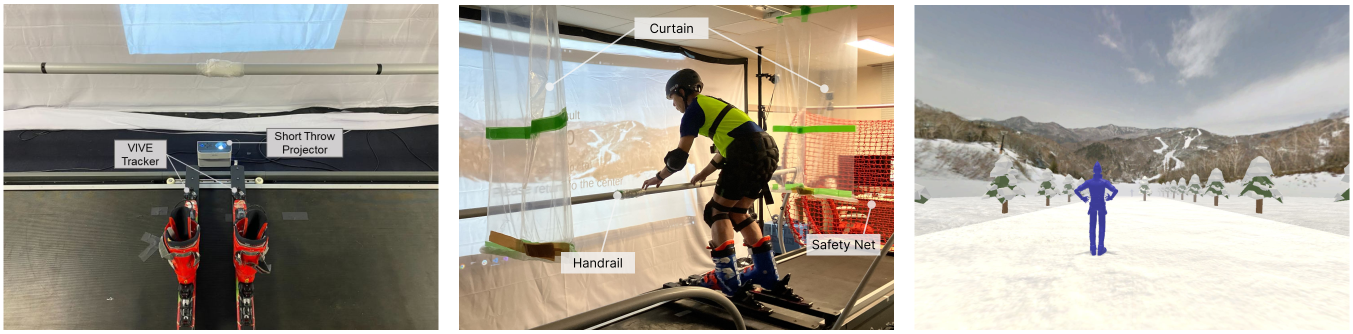
[1] https://www.skytechsport.com
[2] https://www.simsportsarena.com/us-ski-team



(a) Hardware setup on the simulator. **(b) User study setup with safety device.** **(c) Virtual skiing landscape with obstacles.**

Figure 4: The setup of the system in an indoor environment.

Table 1: Demographic statistics of blind participants.

ID	Age	Gender	Vision level	Years of disability	Years of skiing
P1	55	Male	Fully blind	42	40
P2	43	Male	Fully blind	36	11
P3	62	Male	Fully blind	40	59
P4	60	Female	Fully blind	30	30

Table 2: Demographic statistics of sighted participants who guided blind participants.

ID	Age	Gender	Guided participant	Guiding years
G1	50	Female	P1	1
G2	51	Male	P2	4
G3	59	Female	P3	2
G4	61	Male	P4	1

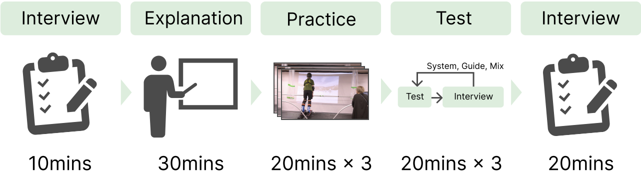


Figure 5: Experimental procedure. In each practice and test phase, users performed the three conditions in random order.

5.4 Procedure

Figure 5 shows the procedure of the experiment. The experiment was conducted in the following steps:

(1): Participants were interviewed about their skiing experience prior to the experiment.
(2): An explanation of the ski simulator and the experiment's content was provided.
(3): For each condition (Guide, System, Mix), participants practiced avoiding obstacles for 20 minutes.
(4): Three measurements were taken for each condition, followed by a trust survey regarding the system.
(5): After the experiment, participants completed a detailed questionnaire about their experiences, insights, and feedback.

To minimize learning effects, the experimental conditions (Guide, System, Mix) were counterbalanced. Additionally, to prevent mutual influence, the interviews were conducted orally with blind skiers and guides placed in separate rooms.

6 Result

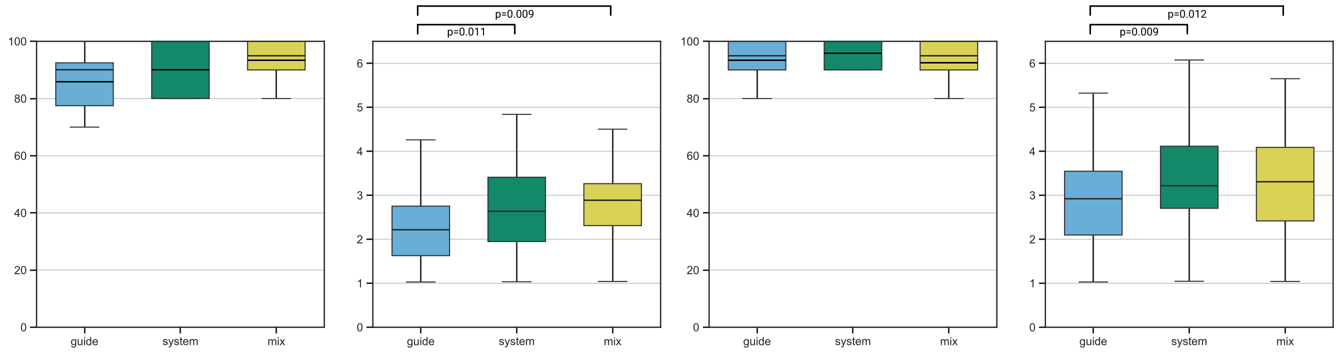
6.1 Safety in Navigation

Figure 6a shows the number of successfully avoided obstacles. Using the system, participants achieved an avoidance rate of 90% ($SD = 0.91$), slightly outperforming the avoidance rate under human guidance, which was 85.8% ($SD = 1.11$). In the condition where the system and human guide collaborated, a stable avoidance rate of 93.3% ($SD = 0.75$) was observed. A Friedman test was conducted to analytically compare the three conditions, but no significant differences were found in the average success rates between conditions ($p = 0.09 > 0.05$).

Figure 6b illustrates the average minimum distance from obstacles. With the system, participants maintained an average distance of 2.69m ($SD = 0.98$), which is safer than the average distance under human guidance, 2.26m ($SD = 0.81$). The Friedman test indicated significant differences between conditions ($p = 0.009 < 0.05$). Pairwise comparisons revealed that the system-only condition was significantly better than human-only guidance (System, Mix: $p = 0.011, 0.009$). This result suggests that the system could estimate obstacle distances more accurately than humans, enabling safer route suggestions.

A similar trend was observed in the experiments with sighted participants. Figure 6c shows the number of successfully avoided obstacles for sighted participants. There were no significant differences in avoidance rates between conditions. This could be attributed to reduced movement on the ski simulator compared to blind skiers, likely due to heightened anxiety caused by the blindfold. The average movement speed on the simulator was 4.2 m/s for blind participants, compared to 3.6 m/s for sighted participants wearing blindfolds.

Figure 6d illustrates the average shortest distance from obstacles for sighted participants. With human guidance, the average distance was 2.88m ($SD = 1.05$), whereas participants maintained



(a) Avoidance Success Rate: Blind Skiers (%). **(b) Distance Measurement: Blind Skiers (m).** **(c) Avoidance Success Rate: Blindfolded Skiers (%).** **(d) Distance Measurement: Blindfolded Skiers (m).**

Figure 6: The average obstacle avoidance rate and the shortest distance to obstacles under each experimental condition.

an average distance of 3.37m ($SD = 1.08$) when using the system. The Friedman test revealed significant differences between conditions ($p = 0.009 < 0.05$), and pairwise comparisons showed that conditions utilizing the system were significantly better than the human-only guidance condition (System, Mix: $p = 0.009, 0.012$). However, no significant difference was found between the System and Mix conditions ($p = 0.38 > 0.05$).

6.2 Auditory Feedback

Table 3 presents the results of the questionnaire survey. **Q1** addresses opinions on the reliability of the auditory feedback. While its reliability was slightly lower compared to human guidance, none of the participants in the experiment expressed the fear of silence, which was a common concern in the preliminary experiment. **Q2** examines the effectiveness of pitch variation. The questionnaire responses averaged 4.0/5 for blind participants and 4.3/5 for sighted participants. Although preferences and familiarity varied among individuals, the pitch variation was generally considered effective. **Q3** focuses on feedback regarding obstacle alerts. Similar to the preliminary experiment, participants noted that relying solely on alerts made turns difficult.

6.3 Workload, SUS, and Trust

Figure 7a shows the SUS scores across the different conditions. The SUS score for the System condition was 74.2 (> 68), which is considered "Good." Although the data is limited in sample size, no significant differences were observed between the conditions. Prior to the experiment, it was hypothesized that the Guide condition would yield higher scores, as PVI skiers are accustomed to human guides. However, the results showed no substantial difference, with the Mix condition slightly outperforming the others. In the Guide condition, significant variability was observed, likely influenced by the skill of the guide and compatibility between the guide and the skier. In the System and Mix conditions, auditory feedback was provided for both obstacle avoidance and collisions. In contrast, in the Guide condition, whether or not feedback about collisions was provided depended on the guide's discretion. This may have introduced bias into the SUS scores for the Guide condition. Figure 7c presents the SUS scores for sighted participants wearing blindfolds. Similar to the blind skier results, the SUS score for the System condition was 73.7 (> 68), also considered "Good." Unlike the blind skier group, the variability in the Guide condition was smaller, as the same guides assisted the sighted participants.

Figures 7b and 7d show the results of the NASA-TLX workload assessment. No significant differences were observed between conditions. When comparing blind participants with sighted participants wearing blindfolds, the latter exhibited a tendency toward higher workload, potentially due to fear and lack of familiarity with being blindfolded. Post-experiment, three of the blindfolded sighted participants reported experiencing motion sickness.

6.4 Qalitative Feedback

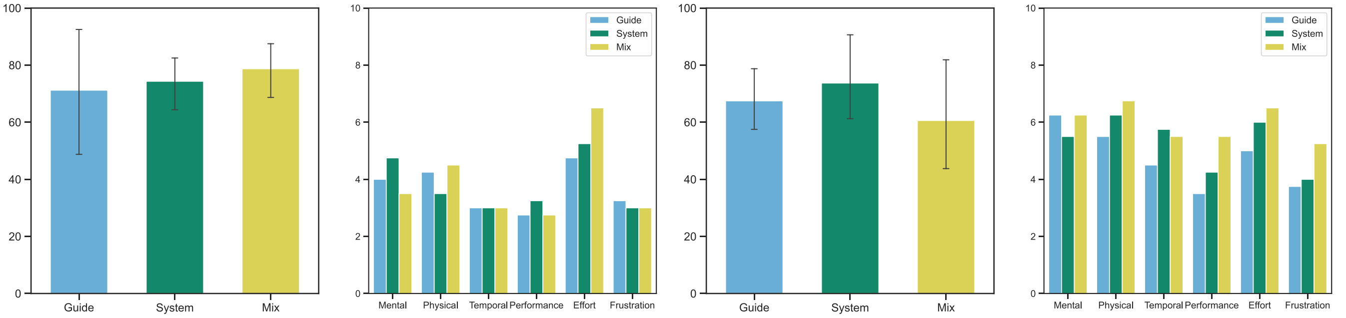
6.4.1 Experience with Turn Guidance by the System. All participants agreed that continuous turn feedback provided a sense of security: **C1** (Comment Number 1): "The continuous sound made it clear that the system was functioning." (**P3**), **C2**: "Knowing I just needed to keep moving forward reduced my anxiety." (**P3**) They also agreed that the turn directions were intuitive. Three participants (**P1**, **P2**, **P3**) noted that pitch changes were effective in understanding the width of turns: **C3**: "I could adjust the turn width in my own way based on the pitch." (**P1**).

On the other hand, **P4** mentioned difficulty in imagining the width of the turns and stated: **C4**: "Even with a human voice, it's difficult to imagine the width of a turn. At best, I could distinguish between large, medium, and small turns." Two participants (**P2**, **P4**) reported occasional confusion during system-guided turn transitions: **C5**: "There were times when I didn't know how long the turn would last." (**P2**) and, **C6**: "I sometimes panicked when the turn direction suddenly switched." (**P4**)

6.4.2 Challenges with Human Guidance. Overall, participants highlighted compatibility issues with human guides: **C7**: "Human guides require time for training. The quality of guidance also varies by person. With a trusted guide, I can focus on enjoying the skiing." (**P4**), **C8**: "Compared to human guides, the system's instructions feel more stable" (**G3**)

Table 3: Likert Items (1: strongly disagree, 5: strongly agree) and a summary of answers.

Question	Condition	Participants				Mean
		P1	P2	P3	P4	
Q1: I was able to trust the turn instructions.	Guide	5	5	5	5	5.0
	System	4	4	4	3	3.8
	Mix	5	3	5	4	4.3
Q2: Pitch variation was effective for understanding turn width.		5	3	5	3	4.0
Q3: Obstacle alerts are effective for obstacle avoidance.		2	2	4	1	2.3
Q4: I believe this system can be used in actual skiing.		3	4	4	3	3.5
G-Q1: (Guide) The system effectively supported turn guidance.	Mix	4	5	5	5	4.7



(a) SUS scores: Blind Skiers. **(b) NASA-TLX: Blind Skiers.** **(c) SUS scores: Blindfolded Skiers.** **(d) NASA-TLX: Blindfolded Skiers.**

Figure 7: Average results of SUS score and NASA-TLX under each experimental condition.

Human guides occasionally made errors in instructions. For example, during simulator practice, some guides mixed up left and right (**G2**, **G3**). Immediate instructions posed further challenges: **C9**: "In sudden dangers, guides hesitate over left or right, and while they say 'uh,' a collision can occur." (**G1**) Moreover, the interpretation of directional instructions was not always consistent: **C10**: "When told 'right,' the skier needs to confirm with the guide whether that means turning right or putting weight on the right foot to move left." (**P3**)

It also became clear that guiding someone to pass through a specific position while turning is challenging for human guides: **C11**: "The system is good at giving turn instructions to avoid obstacles. With a human guide, it's difficult to direct someone to a specific position." (**G2**)

6.4.3 Experience of Collaboration Between Human and System. All guides agreed that the system was helpful in assisting their guidance: **C12**: "By leaving certain tasks to the system, my workload was reduced by half." (**G3**) **G2** commented on the safety aspect: **C13**: "The system can provide instructions faster than a human in sudden situations." During the experiment, some guides delegated turn instructions to the system while providing verbal support about the skier's turning tendencies and speed (**G1**). Additionally, **P3** highlighted the usefulness of a system designed for guides, stating: **C14**: "Verbal instructions from guides can be hard to hear due to snow or wind, but earphones would make them easier to understand." However, **G1** expressed difficulty in overriding the system's instructions: **C15**: "If the path I imagine differs from the system's prediction, intervening midway could confuse the skier."

6.4.4 Expandability of Feedback by the System. Overall, participants raised negative opinions about warning sounds that indicate approaching obstacles: **C16**: "It's difficult to distinguish between turn instructions and warning sounds." (**P1**), **C17**: "Hearing a warning sound might make me nervous and unable to perform my usual turns." (**P2**) **P3** suggested a potential use for warning sounds: **C18**: "While it's hard to use them for turns, they might be helpful for braking or stopping."

Two participants (**P3**, **P4**) suggested feedback they would like the system to provide, such as information on course width and their position: **C19**: "In areas without obstacles, I can navigate by relying on the sound of the ski lift to understand my position, allowing me to ski without specific turn instructions." (**P3**) **C20**: "Being able to imagine the course width would help me turn with confidence." (**P4**) Regarding human guidance, participants emphasized the importance of conveying slope and course information before starting: **C21**: "Before starting, I explain how to navigate through the course." (**G1**)

7 Discussion

7.1 Prototype Safety

In simulation experiments, skiers guided by the System avoided obstacles as effectively as those guided by a human. Notably, the system demonstrated the ability to provide natural guidance by accurately predicting the distance to obstacles and the required turn size, enabling obstacle avoidance while turning. The system's instructions offered the advantage of quantitatively specifying both the direction and magnitude of movement, making it easier to guide skiers along intended routes (**C12**). This capability extends beyond obstacle avoidance, supporting tasks such as gate navigation and turn width adjustments.

Although the experiments were conducted in a simulated environment, participants maintained greater distances from obstacles compared to human-guided skiing. A similar trend was observed in experiments with blindfolded sighted participants. Their feedback response times and turning speeds varied among individual skiers. Specifically, blindfolded sighted participants exhibited slower simulator speeds (0.6 m/s slower) compared to blind skiers. Despite these differences, the system consistently ensured safety. These findings suggest that the system effectively adjusts routes based on individual skill levels and largely supports hypothesis $H2$.

Human guides exhibit significant individual differences in their ability to provide instructions and ski, often requiring skills far beyond those of blind skiers. As a result, finding an appropriate guide can be challenging (**C7**, **C8**). The large variation in the SUS results for blind skiers suggests compatibility issues between guides and blind skiers. In contrast, SlopeNav, a wearable system, has the potential to improve both safety and skiing independence. It can provide consistent instructions regardless of the guide's proximity or emotional state and may even offer faster and safer immediate responses in hazardous situations. Human guides often struggle to give timely instructions in sudden dangers, leading to collisions during moments of hesitation (**C9**, **C13**). Furthermore, the system could be useful as a training tool for beginner guides, offering support while they develop their skills.

7.2 Auditory Feedback Superiority

We evaluated participants' opinions on auditory feedback. Participants reported that continuous feedback through pitch changes provided useful references for turn width and a sense of reassurance (**C1**, **C2**, **C3**). This finding is also supported by the results of the Likert-scale questionnaire (**Q1**, **Q2**). Unlike previous evaluations of CES [27], none of our participants reported excessive noise. This may be due to differences in reference points: CES adjusts sound based on deviations from a course center, causing frequent changes, whereas our system anchors to the next turn initiation point, resulting in smoother transitions and a more stable auditory experience. Although the sense of security provided by auditory feedback does not yet match that of a human voice guide, hypothesis $H1$ is generally supported.

Additionally, it was found that instructions using warning sounds alone are difficult to utilize because they do not convey specific methods for obstacle avoidance. Even when combining turn instructions with warning sounds, the increased number of auditory cues made it harder to distinguish between them, highlighting the need for a well-designed auditory feedback system (**Q3**, **C17**, **C18**). To enable blind skiers to navigate a course freely, feedback that conveys their position within the course, rather than warning sounds, may be more effective (**C20**). Furthermore, integrating other modalities, such as haptic feedback on the arms or face, could provide clearer guidance. Verbal instructions might also be beneficial, particularly for conveying partial information in a more intuitive manner (**C21**). These findings underscore the effectiveness of continuous auditory feedback in providing spatial awareness and guiding navigation, while suggesting that the integration of supplementary modalities could further enhance its clarity and usability.

7.3 The Potential for Collaboration Between Human Guides and SlopeNav

To advance semi-automated guidance on real snow, we evaluated the collaboration between guides and the system. Guides agreed that the system effectively supported their tasks (**G-Q1**, **C12**, **C14**). By handling repetitive instructions like turn guidance, the system allowed guides to focus on more flexible tasks, such as discussing snow conditions or scenery (**C21**). However, some participants experienced confusion when instructions were overridden in the MIX condition. Skiers accustomed to the system's guidance were occasionally startled by abrupt changes in instructions (**C6**). Similarly, guides faced difficulties determining the right timing to override the system (**C15**). To address these issues, it is crucial to establish a clear division of roles between the system and the guide and to enable the system to interpret the guide's intentions.

7.4 Limitations and Future Work

While our results underscore the potential of SlopeNav, we acknowledge existing challenges and have identified several avenues for further exploration.

First, SlopeNav is still the first step in bridging simulated blind skiing with real skiing, and it has not yet been tested under real-world conditions. To ensure its robustness in environments, it is essential to account for external challenges, such as environmental noise. Combining stereo cameras and LiDAR sensors could enable more reliable obstacle detection. Additionally, the current system does not account for dynamic obstacles and constructs paths solely based on the detected coordinates at the time of observation. Incorporating predictions of obstacle movement could enable the construction of safer routes. Moreover, the current system focuses on local path planning. To apply it in real ski resorts, we plan to integrate global path planning based on GPS and course information.

Second, the current system lacks sufficient consideration for the skier's speed, due to the simulator's limitations in handling braking. Feedback related to braking needs to be added. Post-experiment interviews revealed that, in real skiing, guides instruct skiers to perform slightly uphill turns to decelerate or, in emergencies, advise them to fall to stop. Improving route construction and braking instructions could enhance safety.

Third, the system does not yet fully consider individual skier-specific turning tendencies in route planning. Posture during a turn is a key factor in determining the optimal timing for the next turn instruction. While providing instructions immediately after a turn is ideal, doing so mid-turn when the skier's body is tilted can be challenging. Incorporating not only movement paths but also information on the skier's center of gravity and posture could enable smoother and more intuitive guidance. Additionally, IMU sensors and insole-based foot pressure sensors could be useful for estimating the skier's posture and turning dynamics.

Lastly, the small sample size in our study is a notable limitation. To mitigate demographic biases such as age distribution, we plan to recruit a more diverse range of participants. Expanding the participant pool will help refine the system for broader applicability. Moving forward, we will continue improving the system based on user feedback.

8 Conclusion

In this study, we introduce SlopeNav, an auditory feedback prototype designed to enable blind skiers to ski safely while executing natural turns. Through indoor user testing, we verified the effectiveness of continuous turn guidance and skill-adaptive route planning, demonstrating a level of safety comparable to that provided by human guides. Additionally, we developed and validated a collaboration function between guides and the system for practical use in real-world environments. These findings pave the way toward reducing the reliance on skilled guides and enabling blind individuals to ski independently.

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