Reproducible Sonification for Virtual Navigation

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ABSTRACT

The use of sonification for navigation, localization and obstacle avoidance is considered to be one of the most important tasks in auditory display research for its potential application to navigation systems in vehicles and smartphones, assistive technology and other eyes-free applications. The aim of this technology is to deliver location-based information to support navigation through sound. In this paper a comparison of two sonification methods for navigation and obstacle avoidance is presented. These methods were initially developed during a sonification hack day that was ran during the Interactive Sonification (ISon) workshop 2013. In order to allow the formal comparison of methods, we followed a reproducible sonification approach using a set of guidelines provided by SonEX (Sonification Evaluation eXchange). SonEX is a community-based environment that enables the definition and evaluation of standardized tasks, supporting open science standards and reproducible research. In order to allow for reproducible research, the system has been made publicly available.

Keywords: interactive sonification, auditory displays, spatial auditory displays, blind navigation, reproducibility.

1 INTRODUCTION

Auditory Displays are systems that transform data into sound and present this information to the user using an interface that allows them to interact with the sound synthesis process. This transformation of data into sound is called sonification, which can be defined as the systematic data-dependent generation of sound in a way that reflects objective properties of the input data [8].

Auditory displays make use of the ability of our auditory sense to interpret the information encoded by the sonification algorithm. Auditory displays exploit our powerful auditory sense [14] to develop systems where audio is the main carrier of information in a broad sense. Many examples can be found in the literature, including auditory displays in exercise sports, and rehabilitation [16], aircraft flying [13, 17], data exploration, and industrial process monitoring [11].

Sonification for visual substitution, navigation, target localization and obstacle avoidance are topics of great importance in auditory display research due to their potential application to navigation systems in vehicles and smartphones, assistive technology for the visually impaired and other eyes-free applications. The aim of these technologies is to deliver location-based information to support navigation through sound. However, this is a very challenging task as discussed in [5]. The main challenge is to design a meaningful auditory display that is able to communicate relevant aspects of complex visual scenes, where psychoacoustics and aesthetics are very important design factors. The resulting sound must be accurate in terms of the location-based information communicated but it has to be also attractive to the user.

Multiple sonification methods for assisted navigation can be found in the literature, and a good review of these is covered in [5]. In general, these methods scan the space looking for obstacles and synthesize the position and other properties of the scene using different sound rendering modes [1, 6, 18]. A common approach is also to use spatial audio to represent spatial data [15].

Despite all this work, a robust evaluation and comparison of the effectiveness of sonification methods is often neglected (as shown in [3]). Sonification research is, in many cases, not reproducible as defined in [19] and, as a consequence, Auditory Display researchers do not have a baseline for comparison. The selection of sonification techniques (either parameter-mapping [7] or model-based sonification [9], for example) and their corresponding parameters is based on subjective criteria in most of the cases.

To overcome the existing limitations in the design and formal evaluation of sonification methods, an evaluation exchange framework for reproducible sonification named SonEX (Sonification Evaluation eXchange) was defined in [3]. Note that we center our discussion about the sonification algorithm itself, the transform used to render the sound from the data, and not the whole auditory display [8]. The idea of being able to compare the performance of multiple sonification algorithms under a number of agreed conditions and performance measures is what we call *reproducible sonification*.

Following SonEX guidelines, a call for participation for a blind-navigation task was proposed during the sonification hack day that was undertaken at the 2013 Interactive Sonification (ISon) workshop [1] held at Fraunhofer IIS, Germany, in December 2013 [2]. In this task, subjects were tasked with guiding an avatar to a target point avoiding obstacles using only auditory cues. Researchers submitting algorithms for evaluation interfaced with the platform by receiving information about the position and properties of the obstacles and transforming this information into the best possible auditory representation.

A formal evaluation of the algorithms proposed during the ISon 2013 is presented in this paper. The navigation task has been implemented in the form of a virtual environment (a formal game) which has been made publicly available [2]. This work constitutes a first application example and many other tasks could be defined following SonEX [3] enabling reproducible sonification research. This paper is also the result of the collaboration between Swansea University, The University of York, Zürich University of the Arts and Fraunhofer IIS.

The outline of the paper is as follows. Section 2 introduces the interactive sonification virtual environment proposed for a blind-navigation task during the hack day celebrated together with the ISon 2013. The sonification algorithms proposed during this hack

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[1] http://interactive-sonification.org/ISon2013/
[2] Public link to be released.

day and submitted for evaluation are presented in Section 3 . Then, Section 4 describes how the sonification methods are evaluated. Results are discussed in Section 5. And finally, conclusions and future work are presented in Section 6.

2 An Interactive Sonification Virtual Environment for Reproducible Sonification

As opposed to regular sonifiction, *interactive* sonification is concerned with the use of sound to encode information when there is a person at the heart of an interactive control loop. The 4th Interactive Sonification (ISon 2013) Workshop was run at Fraunhofer IIS in Erlangen, Germany, and gathered experts on this very specific research topic. The workshop included submissions, that dealt with interfaces between humans and auditory displays, perceptual aspects of the display, new platforms and applications of interactive sonification and more.

This year, the conference paid special attention to the topics of pervasive computing and reproducible research. Reproducible research was successfully applied in many research areas but its application in the context of interactive sonification might be challenging. Among other problems which are discussed in more detail in [3], the definition of the sonification task might be difficult to measure, also the replication of exactly the same conditions for evaluation and comparison is complicated, and subjective evaluations must be performed in most of the cases. Still, reproducibility is a very important issue in sonification research if we want to develop well-stablished sonification methods and standards for data display and analysis [10].

In order to promote reproducible research in the context of sonification, a hack day was organized during the ISon 2013. The system was defined according SonEX (Sonification Evaluation eXchange) guidelines [3] and the proposed exercise was an audio-based blind navigation task. The system has been made publicly available to promote the reproducibility of the results [3]. These topics, together with a general description of the system, are introduced in the following subsections.

2.1 System Description

Figure 2.1 shows a simplified block diagram of the proposed evaluation system. The system has been developed in Python using Panda3D libraries for rendering the 3D virtual environment [4] and pyOSC, which is a Python implementation of the OSC (Open Sound Control) protocol [5], for sending the data to the sonification algorithms. The main elements of the system are the *Task*, the *Sonification* method and the *User* that evaluates the sonification method.

The *Task* block, which we call the *Walking Game*, constitutes the core of the system and implements the virtual environment for the blind-navigation task described next. The *Sonification* module is developed by the researchers participating in the benchmarking task. This *Sonification* block is the one in charge of synthesizing the sound given information about the scene. The scene description is sent to the *Sonification* agent by the *Task* block using a predefined set of OSC commands. These commands are used to send information such as the position of the avatar and the position and size of the obstacles. This set of commands define an abstract *Interface* (also shown in Figure 2.1) between the sonification method (the solution) and the task (the problem) such that researchers can develop their algorithms independently of the specific implementation details of the virtual environment. Hence, researchers are then able to use Pure Data, SuperCollider, CSound or any other sound synthesis software to implement their sonification proposal. A list of the commands available can be found in [2].

[3]Public link to be released.
[4]http://www.panda3d.org
[5]http://opensoundcontrol.org

Finally, the *User* directs the avatar using a keyboard for *Interaction* and the audio feedback provided by the sonification system using a pair of headphones. The virtual environment (the position of the avatar) is updated according to this interaction.

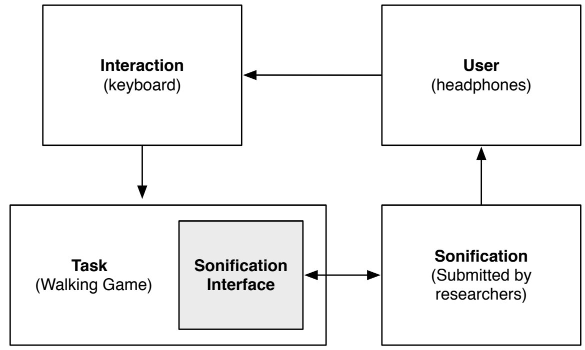

Figure 1: Block diagram of the proposed system. Researchers submit their sonification algorithms for evaluation.

2.2 Task Description

The system developed for this experiment provides a virtual environment where subjects must guide an avatar to a target point using only auditory cues in a computer. Figure 2 shows an image of the virtual environment to be sonified, where several obstacles and the target point are shown. A demonstration video is also provided in to better understand the experiment [6].

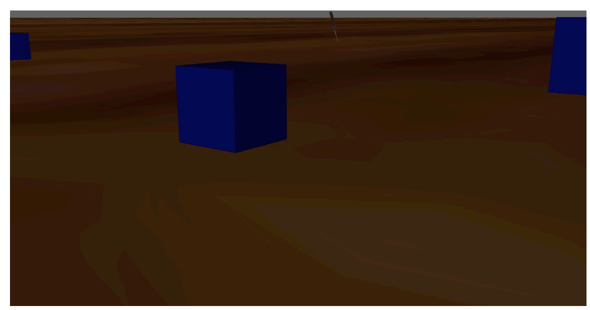

Figure 2: A virtual environment for the evaluation of sonification algorithms for a blind-navigation task. Several obstacles and the target point are shown.

The virtual space is visually presented to the test user together with the sonification of the scene on a screen. At some point, no visual information is provided and the subject must guide the avatar using auditory information alone. The sound is displayed using stereo headphones and the avatar is controlled using the cursor keys in a keyboard. More advanced interfaces such as handheld smartphones equipped with a compass module could be defined in the future.

2.3 SonEX for Reproducible Sonification

SonEX (Sonification Evaluation eXchange) is a framework that allows for the definition of a number of standardized sonification tasks and their corresponding evaluation measures for algorithm benchmarking [3]. In SonEX, the tasks are collaboratively defined by the members of the community and independently evaluated, ranking sonification techniques according to their statistical performance. SonEX has adopted many of the ideas implemented in

[6]`https://db.tt/4Lp9JdIc`

the Music Information Retrieval Evaluation eXchange(MIREX) [4] looking for the same success. MIREX has been running since 2005 and has significantly contributed to the development of new and very competitive systems.

Following the workflow guidelines defined for SonEX, a call of interest for the navigation sonification tasks was submitted to ISon 2013 community after the notification of paper acceptance. More than 10 sonification researchers participated in the hack day.

The task described in Section 2.2 was defined before the ISon but it was slightly modified according to the suggestions of the participants. It was also agreed to evaluate sonification methods in terms of the number of times the target has been reached, the distance to the target relative to the original position, the number of collisions with obstacles and sonification preference. Finally, the OSC sonification interface described in [2] was discussed and extended according to researchers needs.

The development and evaluation of the algorithms was planned to be done during the hack day. However, there was no time enough to complete the whole experiment. Still, 2 participants decided to keep working on the task and submit their algorithms for evaluation after the ISon. Another extra algorithm is currently under development.

The use of a common definition of the task, the abstract interface used and the agreed evaluation measurements, enables the comparison of algorithms, overcoming the lack of formal analysis and comparison observed in sonification research.

3 Interactive Sonification Methods

Two different methods were submitted for evaluation. The first one, proposed together by Timothy Neate and Jiajun Yang from Swansea University and the University of York respectively, is based on a grain based sonification, where pitch is reduced as we get closer to the target. The second one, developed by Andrés Villa-Torres at Zürich University of the Arts, is based on a panned pulsating sound whose pitch increases as we get closer to the target. Next, a detailed description of these sonification methods is presented.

3.1 Neate-Yang Method - Swansea & York

When developing an algorithm for the Walking Game visually, we generally use the following tactics: first, we walk and turn to get the target within our visual field. At the same time, we also look at the obstacles in front of the avatar. When finding the target, we normally pick the shortest route, which means facing toward the target by turning and then walking straight to it. This is the ideal scenario. However, there is a reasonable chance that a few obstacles will be in the way.

Ideally, when creating an auditory feedback system for an obstacle evasion task, we should create a 'mental route' for the user to navigate towards the target. However, problems arise if we wish to simulate this visual method sonically. The main problem is that, visually, we are capable of perceiving the location of multiple obstacles serially to quickly figure out a route to the target.

This sonification method does not try to simulate the visual senses for this task, but uses a more sonically appropriate method, including three main mapping methods: a distance mapping, a directional mapping, and a collision detection mapping.

3.1.1 Distance-to-target mapping

A distance-to-target mapping was implemented such that the user can determine how far they are away from the target. From the auditory feedback they get when they move in a specific direction, the user can determine how they are performing. This creates a positive, or negative, feedback loop as they move.

The mapping used was a simple oscillator mapped linearly to distance, meaning that as the user gets closer to the target, the frequency of the oscillator gets lower. This mapping was chosen because we are able to detect the subtle differences in frequency with ease [21]. The sound is triggered as a form of pulse train rather than a continuous pitch, as this was found to be more pleasant to listen to, and because pulse trains have been shown to be effective when used to represent distance [20]. The note interval was proportional to the distance as the user does not need to hear the sound as frequently as they will have more time to react.

3.1.2 Directional Mapping

With regards to the directional mapping, it was decided that simply telling the user if they are in line with the target would be enough. The user is rewarded by being in line with a soothing amplitude-modulated tone. The tone plays when the user is facing towards the target (0°), and when the user is facing away (180°), within some threshold. They can then use the distance mapping to determine which is the correct direction.

This mapping was achieved by calculating the difference between the walking angle and the angle of the current avatar location to the target, when related to the coordinate plane. The unit of the difference is in degrees, and the value is looped every 180°. Additionally, the angular difference helps us determine whether the avatar is moving to the right or to the left to the target and can therefore be mapped to control the panning of the to determine the direction.

3.1.3 Obstacle Detection

To detect obstacles, a 'virtual white cane' zone was implemented. This involved detecting if there was some obstacle within some distance of the user (around 360°), meaning that when they approach an obstacle on any side, they are aware of it, and from their previous heading should be aware of its approximate location. This was implemented by comparing the user's current position, and determining the distance between it and all obstacles, and if there was an obstacle within the zone an alert was triggered.

The sound used for this alert was a sequence of two notes (Fsharp and its perfect fourth) with an interval of 150ms. This interval was chosen because it was felt that it's a relatively comfortable sequence of notes to listen to, but still portrayed the intended urgency. The timbre of the sound was shaped by a FM based synthesis so that it contained a rich spectrum, to differentiate it from the other sounds in the system. The sound is also smoothened by a fix amplitude envelop.

3.1.4 Using the System - A Walkthrough

The following scenario describes how the three complementary mappings should be used to operate the feedback system:

When the user is spawned in the environment they should listen for a repeating tone (the distance-to-target mapping). By listening to its frequency, and its rate of repetition, it should be possible to determine how far away they are from the target – if it's a low frequency they are close, and if it is high they are far away. The user should then rotate to determine their alignment. Using the directional mapping, and the distance-to-target mapping, they should be able to determine the best linear path to the target. Using the obstacle detection mapping it should be possible to avoid any collisions with obstacles on this path. Figure 3 describes this system graphically. When the user has found the target an auditory alarm (a repeating saw-tooth sound) is played to notify them of this.

3.2 Villa's Method - Zürich University of the Arts

In the task in case, the available movements are forward, right rotation and left rotation. These limitations transform the 3D space in a two dimensional plane. There are some obstacles in the way, which block the straight line between the player and the target and make harder for the user to find the right path.

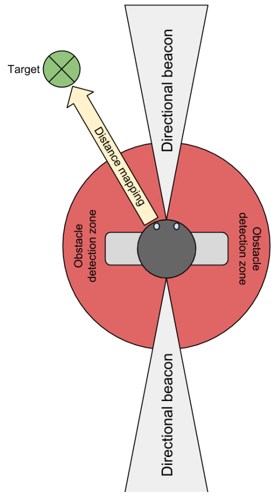

Figure 3: Sonification model proposed by Swansea University and the University of York.

The proposed sonification method uses three values provided by the game engine in order to trigger sounds: linear distance between target and player, linear distances between objects and player and the angular distance between player and obstacle. Processing is used as a OSC bridge between the game and Supercollider, which is used for value interpretation and virtual sound generation.

3.2.1 Target object sonification

When the game starts a pulsating sound representing the target emerges. The pitch and the speed from the pulsating sound increases, as the distance between the target and the player becomes shorter.

Since the available movements are constrained to a two dimensional plane, these three dimensional coordinates provided by the game for player and target are simplified by discarding the value on the y axis, and transforming the x and z values into a two dimensional plane (observe Figure 4).

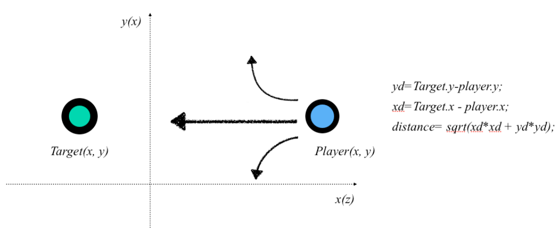

Figure 4: Possible movements from player and the targets distance calculation.

Thus, the distance is calculated as a two dimensional vector difference. The resulting value is inversely and linearly mapped to the pitch in a range between 50 to 800 Hz as well as to a pulse repetition interval between 0.5 to 0.01 seconds. The result is a pulsating sound, which becomes more nervous as the player approaches the target.

3.2.2 Obstacle Collisions

Obstacle collisions are detected by calculating each single distance between player and obstacles. Using these dynamic values the sound engine is able to identify when a distance threshold has been surpassed by the player (observe Figure 5). In this way a collision signal is triggered and a noisy sound emerges. Since the emerging sounds become louder as the player gets closer to the obstacles, the player is potentially able to evade obstacles by avoiding the noisy sounds that become louder. For this, a linear mapping between linear distance and loudness is applied.

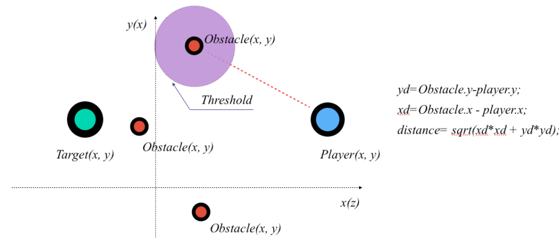

Figure 5: Obstacles distance to player and the threshold rate for sound triggering.

3.2.3 Angular Distance and Panning

To provide the subject with orientation information, its angular position is mapped to a panning value. The angular value is a distance value between two points as observed from a location different from any of those. The target object is set as the observer perspective. The original location from the player is then set as the fixed point A and the current location from the the player is set as the floating point B as Figure 6 shows.

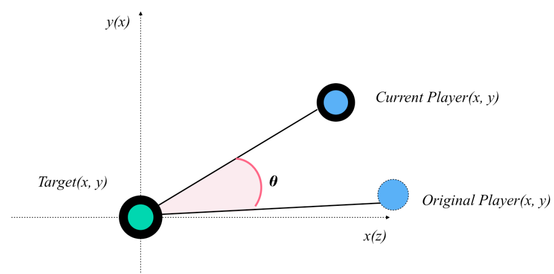

Figure 6: Angular distance between current and old players position.

Finally the angle obtained θ is mapped to the panning value in a rate from -1 to 1. This panning value is applied to a panning function, which affects the stereo output from the target sonification. When the player is far on the right side from the target the target sound will be louder on the left side and vice versa.

4 Evaluation

4.1 Subjective Test Description

In order to evaluate the performance of the submitted sonification methods, a subjective evaluation test was carried out. Subjects played the game described in Section 2 and its activity was recorded. The submissions were evaluated in single sessions which were designed to take no more than 45 minutes per user.

Subjects interacted with the system in two different modes, training and test, which consist of different scenarios where obstacles and target positions are placed at random in the virtual space. During training (2 different scenarios) the user went through two procedures. First, the user was allowed to move the avatar in an audiovisual condition to get familiar with the game itself. The user was expected to understand the aim of the game, keyboard controls and aesthetics of the game such as avatar speed, orientation

Evaluation	Algorithm	
	Neate-Yang	***Villa***
Target found	$62 \in [41,75]$	$0 \in [0,0]$
Distance	$25 \in [11,66]$	$179 \in [149,220]$
Time	$93 \in [82,103]$	$120 \in [120,120]$
Collisions	$62 \in [35,97]$	$20 \in [6,70]$

Table 1: Evaluation results, mean values and bootstrapped 95% confidence intervals. Target found (%), times the subject found the target; Distance (%), distance to the target relative to the starting point; Time (s), time to find the target or time up; Collisions, number of collisions.

and obstacles. Second, the visual information was removed and the user was allowed to guide the avatar using the auditory information alone. Here the user was expected to get familiar with the auditory feedback signals provided by the signification algorithms in sync with keyboard controls. Once the training was done, the user evaluated the sonification algorithm in a test mode (4 different scenarios). This is essentially the same as the second procedure described for the training mode. However this time the evaluation is considered and the activity of the subject is recorded. The user was expected to complete the objective of the game solely with the aid of auditory feedback signal on the different scenes, with obstacles and target positions changing each time. In all the cases, users were given a maximum time of 2 minutes to complete each scene.

4.2 Performance Analysis

The auditory display proposed in this paper has been evaluated in terms of the number of times the target has been reached, the distance to the target relative to the original position, the number of collisions with obstacles and sonification preference. These scores were then used to determine the effect of the auditory feedback on the task by looking at the means and *p-values* based on a t-test analysis [12]. 95% confidences intervals (CI) for the mean values were calculated using bootstrapping [22]. The objective of this experiment was to find out which sonification method helped the participants to best locate the targets and how accurately. As discussed in [3], we are aware that the proposed evaluation does not reflect the details of a real system and that small factors change results when implementing a real auditory display. Still, we believe that this information can be used for discarding algorithms.

The listening test was taken by 8 participants. Given the 4 different random scenes used for evaluation, 32 different values were available for doing the statistical analysis of performance.

4.3 Participant Demographics

All 8 participants were interns or researchers at Fraunhofer IIS. The average age of the participants was 34 years. The group included people of German, Indian, Spanish, Australian and Chinese nationality. With regards to gender only one female took part in the experiment.

Some test-oriented questions were asked. Since the listening test was performed at the Audio Department of Fraunhofer IIS, all subjects had experience with audio at a professional level. Also, most of them had some experience playing games and high experience with computers. In addition, 4 of the subjects had already some experience in the field of sonification. Subjects were also asked to rate how they liked the sonification, from 1 (worst rating) to 5 (best rating), and give honest comments on the experience.

5 Results

A summary of the evaluation results are shown in Table 1. As we can see, participants were able to find the target 62% of the times using *Neate-Yang*'s sonification method. When using *Villa*'s method, subjects were not able to get to the target. Participants spent 93 seconds in average to complete the task when using *Neate-Yang*'s method, but they were not able to find the target in the allowed 2 minutes when using the second algorithm.

Even though subjects were not able to localize the target in every case using *Neate-Yang*'s method, we can see in Table 1 that the relative distance to the target (the final distance divided by the original distance) was reduced to 25%. However, the relative distance increased ($distance > 100\%$) when using *Villa*'s sonification method, meaning that player got lost in the virtual environment. Because there were no obstacles far away from the target, the number of collisions is lower in *Villa*'s case (20 vs 62). In all these cases, the differences in mean were statistically significant ($p\text{-}value < 0.01$).

Looking at *Neate-Yang*'s overall performance, we can say that the method did a good job at communicating the position of the target on time but not to avoid obstacles. The sound alerting about an obstacle occurs suddenly and there is no sense of distance with respect to the objects. Hence, subjects rated this sonification with an average score of 3.5. The obstacle avoidance technique should be therefore improved in further developments.

Some participants claimed that, although they preferred the way *Villa*'s method sonifies the distance to the target, the mapping of the direction in terms of the original position of the avatar with respect to the current position described in Section 3.2.3 was difficult to understand. That was the main reason for *Villa*'s poor performance and people rated this sonfication with lowest score.

6 Conclusions

The method proposed by *Neate-Yang* performed statistically better than *Villa*'s method, however results are still far from being ideal. Therefore, algorithms have to be further developed in order to increase the performance of the systems in terms of accuracy for locating the target and obstacle avoidance.

To the best of our knowledge, this work constitutes the first attempt to develop reproducible interactive sonification for navigation and obstacle avoidance. Researchers interested in this topic can either submit their algorithms for evaluation or run the system on their own to be able to compare results[7]. Note that this experiment constitutes a first SonEX example but this exercise can be extended and other sonification tasks can be proposed. The use of a common definition, an agreement on the interface to be used and the evaluation measurements, enables the comparison of algorithms, overcoming the lack of formal analysis and comparison observed in sonification research.

With regards to future work, we are planning to extend our listening tests such that new sonification developments can be evaluated. These new developments could include the use of binaural audio and new audio synthesis approaches. Also, the complexity of the scene will be a factor to be analyzed. In addition, training effects should be assessed. Finally, the navigation and obstacle avoidance task could be extended to additionally display point of interests. The development of this technology could be potentially used for displaying extra information in maps for both sighted and blind people.

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