Exploring Virtual Environments by Visually Impaired Using a Mixed Reality Cane Without Visual Feedback

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ABSTRACT

Though virtual reality (VR) has been advanced to certain levels of maturity in recent years, the general public, especially the population of the blind and visually impaired (BVI), still cannot enjoy the benefit provided by VR. Current VR accessibility applications have been developed either on expensive head-mounted displays or with extra accessories and mechanisms, which are either not accessible or inconvenient for BVI individuals. In this paper, we present a mobile VR app that enables BVI users to access a virtual environment on an iPhone in order to build their skills of perception and recognition of the virtual environment and the virtual objects in the environment. The app uses the iPhone on a selfie stick to simulate a long cane in VR, and applies Augmented Reality (AR) techniques to track the iPhone's real-time poses in an empty space of the real world, which is then synchronized to the long cane in the VR environment. Due to the use of mixed reality (the integration of VR & AR), we call it the Mixed Reality cane (***MR Cane***), which provides BVI users auditory and vibrotactile feedback whenever the virtual cane comes in contact with objects in VR. Thus, the MR Cane allows BVI individuals to interact with the virtual objects and identify approximate sizes and locations of the objects in the virtual environment. We performed preliminary user studies with blind-folded participants to investigate the effectiveness of the proposed mobile approach and the results indicate that the proposed MR Cane could be effective to help BVI individuals in understanding the interaction with virtual objects and exploring 3D virtual environments. The MR Cane concept can be extended to new applications of navigation, training and entertainment for BVI individuals without more significant efforts.

Keywords: Virtual Reality, Mixed Reality, Visually Impaired, Spatial Exploration

Index Terms: Human-centered computing—Human computer interaction—Interaction paradigms—Mixed / augmented reality

1 INTRODUCTION

Virtual Reality (VR) technology has presented great potential in various aspects of our life, such as entertainment, education, yet the accessibility in VR remains a significant challenge for the blind and visually impaired (BVI) due to the majority VR systems relying on visual feedback. Recent years, multiple promising researches and systems have been conducted and developed to assist BVI individuals for a better quality of life using VR with non-visual feedback, usually aiming at orientation and mobility (O&M) training. However, these systems often only work in a lab environment and therefore are not accessible to the large visually impaired community. Therefore, little have BVI individuals known, understood and had a chance to experience VR.

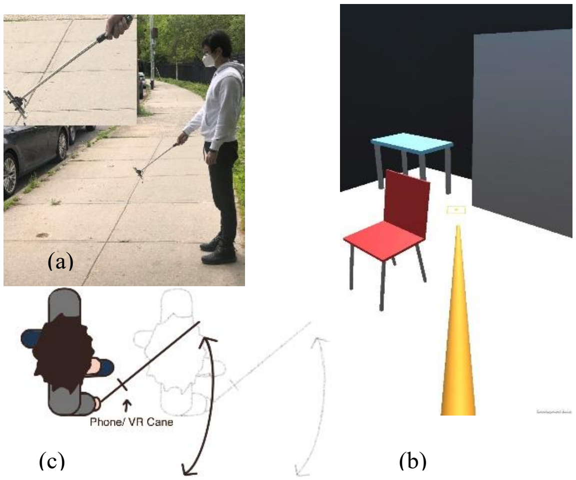

Figure 1. A sighted user is evaluating the proposed MR Cane in a real-world space as shown in (a) top-left and Its corresponding VR space is shown in (b), and a top-down view of the VR exploration is shown in (c).

Motivated by the need of BVI individuals to learn, we propose a free-walk Mixed Reality Cane (***MR Cane***) using mobile AR and VR techniques as a first step towards better implementation of mobile VR for BVI individuals. Inspired by Microsoft's Canetroller [14, 18], we propose a mobile VR application for BVI individuals to explore the virtual world via an iPhone by free-walk locomotion, without any complicated mechanisms and high-end VR devices. The MR Cane (Figure 1) uses the iPhone on a selfie stick to simulate a long cane in VR, and utilizes visual inertial odometry provided by Augmented Reality (AR) techniques to track the iPhone's real-time poses in an empty space of the real world, which is then synchronized to the simulated long cane in the VR environment. Using the MR Cane, BVI individuals could scan a virtual environment and interact with the virtual objects in the environment to gain perceptual understanding of spatial information through auditory and vibrotactile feedback in real time, as well as the recognition of the sizes and shapes of virtual objects. In addition, the proposed approach allows users perform free-walk locomotion, which enables them to walk in an empty physical place while exploring the VR world. The purpose of our MR Cane is to introduce BVI individuals the VR concept, help them understand the interaction within the virtual environment, and furthermore, build their skills of perception and recognition of virtual objects and virtual environments. The main contributions to this paper are as follows:

- Propose a Mixed Reality Cane, the first mobile mixed reality virtual cane, based on mobile VR and AR, which allows the large BVI community to easy access to an immersive VR;
- Utilize the simple auditory and haptic feedback only on an iPhone – a low-cost solution to help BVI individuals to effectively interact virtual objects and environments while walking in a real world.

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Due to COVID-19, we were not able to test the MR Cane with BVI users. Instead we evaluated the MR Cane with 6 participants (all sighted people) and found it helped them understand VR environment. Most of them have learned the rough sizes and locations of the virtual objects in the virtual environment we designed.

In the following, we first summarize the previous research related to our study in Section 2, followed by a formative study in Section 3. Then we describe our proposed system design and implementation in Section 4 and present a preliminary experiment and discussion in Section 5. We conclude the paper in Section 6.

2 RELATED WORK

2.1 Space Exploration/Navigation on Desktop VR

The approach of accessibility VR has been well established on different perspectives. Previous research on accessibility of VR allowed virtual technology accessible to BVI individuals, by creating non-visual or visual VR with audio and haptic feedback on desktops with wearable mechanisms.

The virtual environments built on desktops enable the blind and visually impaired people to interact with the virtual world through haptic and auditory feedback [13]. Lahav et al. developed a BlindAid system that allows users to explore virtual maps on a computer equipped with PHANToM and stereo headphones [12]. Sánchez and Sáenz built a software that represents a subway system in a computer to assist orientation and navigation of BVI individuals in the subway network [8]. Evett et al. developed an accessible game to allow exploration of virtual environments via auditory and haptic feedback using Nintendo Wii devices [2]. HOMERE [10] presented a multimodal VR system where users manipulated a cane that connected to a robot arm to control the virtual cane in the desktop virtual environment and explore the spaces via haptics of collision and texture.

Those studies have shown supportive roles in helping BVI users learn spatial information, however, they are not easily accessible to BVIs.

2.2 Simulated White Cane Using VR

The advances in recent VR research and development enable the designs of more immersive VR experience. A few recent works [14-16,18] enable BVI individuals to walk in a VR environment with a simulated white cane. Walking around in the virtual space provides more immersive VR experiences and allows BVI individuals to more effectively acquire spatial knowledge.

Zhao et al. [18] designed a sophisticated cyber-physical device called Canetroller that simulates white cane interactions to allow BVI people to walk in a physical space with various types of feedback to obtain spatial perception. Siu et al. [14] further improved [18] to provide the simulated cane more realistic and abundant feedback. Both works have ingenious designs to provide realistic feedback. But the systems are complex and adopt a head mounted VR device which is often limited to be used in an indoor environment and are not easily scaled up. Our system is related with both designs but with a focus on simulating the white cane solely with a mobile phone on a selfie stick, though with less feedback but offering a much simpler and more lightweight design.

Kreimeier and Götzelmann [15, 16] proposed simulated canes without the space limit by introducing a VR treadmill in the training to overcome the above space limitation, but no thorough analyses of the users' feedback were reported and the systems are not easy access to large BVI community with the need of a treadmill.

2.3 Accessible VR for BVIs Using Smartphones

A survey presented that 95.4% people with visual impairments are using smartphones and 79.9% of them use iOS systems [20]. In addition, recent studies have expanded the potential of accessible VR promises to the platform of smartphones. The vision accessibility technologies on smartphones have benefited the majority of BVI individuals on entertainment, navigation and social networking.

Regal et al. [22] built a mobile location-based game in the virtual world to explore the suitable approach to support O&M training. Zhao et al. [23] designed SeeingVR, a toolkit to enhance the scenes of VR app with visual and audio arguments for low visions. SeeingVR can be easily implemented on a smartphone. Tang et al. [15] proposed a mobile app that enables BVI users to study indoor layout. The closest work to ours is X-road, a mobile VR app with Google cardboard-like viewer, proposed by Thevin et al. [21]. The app provides visual and audio feedback to train BVI users basic O&M skills to cross road. However, BVI users are only allowed to understand the traffic conditions by visual and auditory feedback, hence it does not provide users a richer interaction with the virtual environment. Our system combined the idea of simulated cane and the accessible VR on smartphones, and allows BVI users not only to explore the 3D virtual environment, but also to interact with virtual objects.

3 FORMATIVE STUDY

The prior work [16-18], provided excellent studies to help us understand the challenges of the BVI users to explore VR space using a simulated long cane. This study aims to design a low-cost and lightweight MR mobile app – the MR Cane - for BVI people to a) allow VR experience without visual feedback, and b) improve perception of the virtual objects with the virtual long cane. For achieving this, in addition to learn from the literature, we also conducted a formative study with the blind using interviews, including observing how blind users explored the environment using real white canes, to help us design the system.

3.1 Formative Study: Method

We recruited two participants (all males) with blindness who are taking undergraduate courses and need visit the campus very often. They received orientation and mobility (O&M) training in the beginning of semester and one trainer come to the campus to provide O&M training to help the participants go to each classroom from building entrance. One (B1) is 55 years old and became blind for 15 years ago, and another (B2) is 22 years old and is blind since birth. Both are long cane users.

We first conducted an interview with these two participants. We asked about their ways to obtain perception of the environment and objects in daily life. We then asked their understanding of VR and prior experience with VR and smartphones. We also explained the definition of VR and provided them a mock-up demo version of the MR Cane to try before it had the real functions. Then we asked them to explore real environments with their long canes while we observed their performances in two scenarios. The scenarios include: (1) The exploration of an experiment room with five desks and four chairs; (2) the recognition of the sizes, shapes and textures of a plastic trash can, a paper box and a desktop with long canes. Participants were asked about what they thought and what challenges they had during the two scenarios.

3.2 Formative Study: Findings

(1) *Experience with VR.* We found that both participants had no prior experience with VR and neither of them heard of VR and any VR applications that were designed for the blind as well. However, after we explained what VR is and asked them to play a demo of VR on an experimental phone, they showed great interest in VR and expected to experience a more fully developed VR system.

Both participants indicated the great potential of VR in O&M training and entertainment. B1 said it was very promising that VR could help them better understand the environment after playing a VR demo.

(2) *Perception of the objects with the long cane.* We observed that both participants were able to recognize the objects with their long cane and identified the sizes, shapes and textures of the objects, As B2 said, they preferred to identify the objects with the cane rather than touching them with hands due to safety issues. A long cane can provide more detailed information on the objects. We found that participants used the long cane to trace the outer edge of an object to perceive its shape. For example, both participants could tell the rectangle shape of the box by outlining the out edge of the box. Participants also could identify the textures of the objects by the auditory feedback from the long cane. For example, both participants could perceive the texture of a plastic trashcan and a paper box by hitting the objects with their canes.

4 SYSTEM DESIGN

We design the Mixed Reality Cane using spatial audio and haptic feedback. The MR Cane allows BVI users to freely walk in an empty physical space to explore an unknown virtual environment that could be a digital twin of a real environment. The hardware design is very simple: it only consists of a smartphone (an iPhone in our implementation) on a selfie stick (Fig 1a). The camera/stick's pose is tracked by using the ARKit APIs [1]; the "cane" with the phone is extended from the selfie stick to the tip of the cane along the direction of the selfie stick in the VR to better simulate the real long cane.

BVI users use a wireless headphone to listen to 3D spatial audio when the virtual cane (which is aligned with the smartphone stick) touches an object in the VR space. In addition, the phone generates vibrotactile feedback with different strength and duration according to the surface texture and the speed of the real "cane" when the virtual cane hits a virtual object.

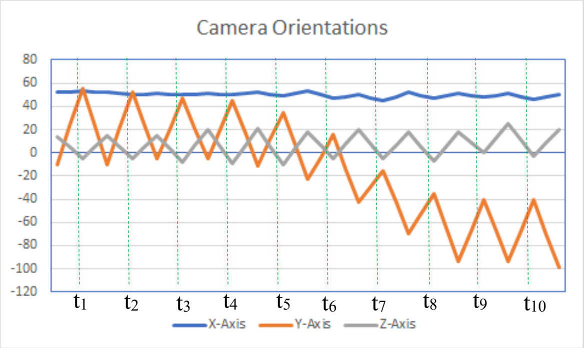

Figure 2. Camera orientation data in x, y, and z axes recorded in 20 seconds. Each cycle represents the cane's one-time movement from left to right and back to left, as shown between two consecutive green dashed lines. Each green dashed line indicates the time of virtual cane reaching to the leftmost position. The vertical axis represents the angles in degrees and the horizontal axis represent time in seconds.

In the previous work, a tracked controller [7,9,14,18] serves as a virtual cane, the 3D auditory and vibrotactile feedback are provided to BVI users when the virtual cane contacts with a virtual object as well as building facility. Auditory feedback is often generated using Google resonance 3D sound [4] according to relative location and orientation between the object and the user's head in the VR space, which is tracked using regular VR head mounted display. However, in the proposed MR Cane system, no additional devices are needed to track the user's head and virtual cane. We use the ARKit to track the smartphone stick whose pose information is passed to the virtual cane in the VR space, and propose a simple solution to track the user's head (Sec. 4.2). Next, we will present the algorithms to track the virtual cane and the user's head.

4.1 Tracking the Cane and Locomotion using AR

The underline visual inertial odometry module of the ARKit on the rear camera tracks the visual features in the real world, and calculates real-time and reliable 6-DOF motion (both translation and rotation) of the smartphone on the stick. Augmented reality requires precise camera pose estimation in order to reliably render a virtual object in the camera's view without a noticeable drift.

When the app starts, the world coordinate systems in both ARKit (in the real scene) and the mobile VR space are synchronized and registered, the physical real-time poses of the camera/cane obtained by ARKit can be transferred to the mobile VR space, so the virtual cane location is updated consistently with respect to the movement of the iPhone. The concept allows BVIs to explore the virtual environment by walking around in the physical space and provides users a more immersive VR experience.

4.2 Head Pose Estimation and 3D Audio

Auditory feedback plays an important role in the VR app, including both head mounted VR and mobile VR, particularly for a VR system without visual feedback. In existing desktop VR solutions [7,9,14,18], the auditory feedback has been carefully designed to help BVI users to explore virtual objects and environments.

The 3D spatial audio simulates how sound waves interact with the user's ears. The time difference between sound wave arrival at the user's left and right ears helps him/her to localize of sound source. The 3D audio [4] can be utilized easily in the desktop VR because the head's 6-DOF (translation and orientation) can be tracked in real time. For a mobile VR, e.g. Google cardboard, the head's 3-DOF motion (orientation) is also tracked using the phone onboard sensors in real time, so the 3D audio can be utilized in the mobile VR applications as well. However, 3D audio is not easily adopted in the proposed system, because the ARKit tracks the smartphone's pose, rather than the user's head (Fig 1).

To solve the pose of users' head, we first estimate the head's orientation. We assume BVI users do not spin their heads while exploring our VR environment, hence both the user's shoulder and head are parts of a rigid object and therefore move consistently. hence, we can just estimate the moving direction of the user's shoulder. We propose the following simple method to estimate the facing direction of user's shoulder, which is equivalent to the user's head, given the phone's poses obtained from ARkit.

Usually a BVI user holds the cane in his/her dominant hand, in front of the body. For a few popular cane techniques, including two-point touch, constant touch or shoreline, the cane is swept left to right in a pattern about shoulder-width. They keep sweeping until the cane hits an object, e.g. obstacle or walls and so on. It often indicates they may have to make a turn and it can be used to confirm the body tracking with a rotation occurs (time $t_5 - t_8$ in Fig 2).

From the observation (Fig 2) we can tell the camera poses updates with repeated cycles when it is swept, each cycle is shown between two vertical dash lines. The user's motion direction can be obtained by calculating the difference of camera's positions between two consecutive cycles. We get the position of the camera when it arrives at the angular limit (either sweep to the leftmost and rightmost), which corresponds to the peak of orientation in y-axis and z-axis. For example, Fig 2 shows the camera orientation data in x, y and z axes collected in 20 seconds. We can calculate body's motion by calculating the difference of camera locations at time t_1 and t_2. The time t_n $(n = 1 \ldots N)$ can be first calculated by measuring the derivative of angular changes:

$$\frac{\partial R_x}{\partial t} + \frac{\partial R_y}{\partial t} + \frac{\partial R_z}{\partial t} = 0 \tag{1}$$

R_x, R_y and R_z represent the orientation angles along x, y and z axes, and can be obtained from the camera pose given by ARKit. By solving Equation (1) we can obtain the time $t_1 \ldots t_k$ and the dominant moving direction of the "cane" (i.e., the camera on the stick) can be obtained by calculating the difference of positions at t_{k-1} and t_k (or include more historical data to get a smoother estimate).

$$\vec{m}_{t_k} = \left[T^x_{t_k}, T^y_{t_k}, T^z_{t_k}\right]^T - \left[T^x_{t_{k-1}}, T^y_{t_{k-1}}, T^z_{t_{k-1}}\right]^T \tag{2}$$

where $\vec{m}_{t_k}$ is a 3D vector that represents the motion direction of the user, which is also considered as the head facing direction.

In Fig 2, the user's motion only includes translations in the cycles $t_1 - t_4$ and $t_9 - t_{10}$, the orientation graphs in x, y, z axes are very similar. In the cycles $t_5 - t_8$, the user's motion includes rotation and we can still obtain the time $t_5 - t_8$ by calculating the derivative of rotation angles using the Equation 1.

Because the "cane" is held by the user and it's safe to assume the constant translation between the average camera/cane's positions (in the middle of the cane's leftmost and rightmost positions when cane is swept) and user's head, which can be calibrated for each user before the experiment. Hence, we solve the problem of head pose, including the constant translation and facing direction.

4.3 VR/AR, Sound and Haptic Implementations

The MR Cane system is implemented using the Unity 3D game engine [24] or the VR design and the Apple ARKit toolkit [1] for cane tracking. To make use of the ARKit toolkit, the system requires an iPhone 7 or up. We selected a popular selfie stick which connects the iPhone via Bluetooth.

To prepare the sound effect, we recorded the sound when using a real white cane to hit or sweep on different floors, including carpet, concrete and wood floors. We also recorded the sound when the cane hits or taps on the different objects with various materials, including plastic, metal, paper. The sound is then played when using the MR Cane according to the speed of the MR Cane in action. After applying the proposed approach to estimate user's poses, we define a sound listener with the estimated pose so a BVI user is able to figure out the object position using the correct 3D spatial sound whenever the virtual cane hits a virtual object. Auditory feedback is generated using Google resonance 3D sound [4] according to relative location and orientation between the object and the user's head in the VR space.

In the current implementation, we include two popular cane techniques in the BVI community: two-point touch and constant touch. Both of them need BVI users to sweep the cane from side to side, with the former only touching the floors on two points (the leftmost and rightmost positions of a sweep), while the latter constantly touching the floor. The MR Cane simulates the haptic feedback of these two cane techniques using iPhone's Core Haptics engine [19].

The application plays an audio warning whenever the MR Cane is too deep inside of an object, but physically stopping the movement of the cane is not possible with our design.

Without external haptic devices, e.g. voice coils, vibration motors, we cannot generate realistic haptic feedback according to different surfaces and textures. We apply some simple vibrotactile using iPhone embedded haptic SDK with different strength according to the speed of the cane motion when the cane hits different objects or sweeps on the floor.

5 EVALUATION

Our goal was to evaluate the usability and effectiveness of MR Cane to obtain perception, recognition and spatial information of an unknown VR environment for BVI users. However, due to COVID-19, we were unable to conduct the evaluation in a short period of time with the BVI users due to the difficulty in training and testing. Instead, to investigate our approach, we conducted a preliminary user study with 6 sighted participants whose ages ranged from 22 to 48 who can easily download the app to their phones and perform the experimental tests. Two of them have VR experience and others have heard about VR but never played with a VR system. All the participants were blindfolded.

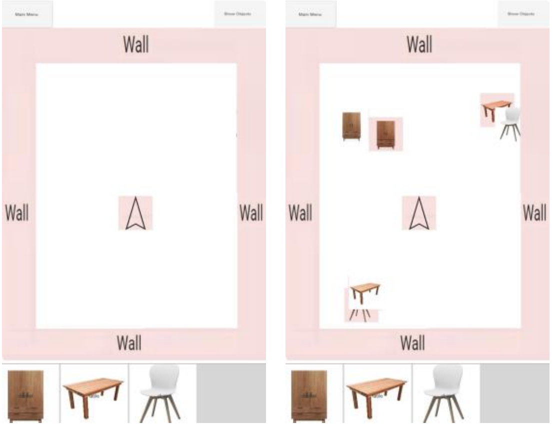

Figure 3. User tests. a) An app interface shows a participant choose the layout of the virtual objects after their VR exploration. (b) A participant correctly identifies the locations of all three objects, but only recognizes the cabinet correctly. The object icons with pink background are true locations (generated randomly in each test), and the object icons white background are participant's answers.

5.1 Method

The virtual room in the experiment is a 30 square meters room with four walls with concrete floor. There were three objects candidates placed in the virtual environment randomly each time, including a metal cabinet, a plastic table with metal legs, a plastic chair with metal legs, the participants are not aware of the number and types of VR objects, as well as the spatial layout of the room before their experiments.(Fig 1b).

All participants conducted experiments in an open space inside and around their house. Each one started with a tutorial session, including a short introduction of long cane techniques, the MR Cane, auditory and vibrotactile feedback that the system produces when the cane comes in contact with different surfaces, followed by the actual exploration in the virtual room with the MR Cane. Participants were informed of the whole procedure of the experiment and they were asked to identify the objects' locations and types in an evaluation module at the end of experiments. Their exploration data, including time, errors, trajectories and the spatial layouts of the virtual objects, were recorded and stored on our server.

We asked participants to explore the room and find virtual objects, they can terminate the experiment whenever they complete the task and then work on the evaluation task. Fig 3a shows an app interface for the evaluation. It allows a participant to place objects in the virtual room (a top-down view) after his/her VR exploration. It renders four walls with the user's facing direction as a reference. We asked the participants to select the objects from the bottom icon list (can select same object multiple times) and put at the location of the 2D room based on the spatial knowledge and object type they learned from the VR exploration. The experiment first evaluated if the participants correctly built mental model of the virtual environment with the MR Cane. Furthermore, it studied how immersive the VR experience was. The participants try to learn different object by various cane feedback while the MR Cane come in contact with different parts of the virtual object. Fig 3b shows that a participant correctly learned the spatial layout of the virtual room (locations of all three virtual objects), but only correctly recognizes the cabinet.

5.2 Preliminary Results

All six sighted but blind-folded participants completed tasks with an average duration of 32 minutes and spent 12 minutes on the tutorial section on average.

Effectiveness of Spatial Knowledge Learning

All six participants were able to find all the three virtual objects in the room with the MR Cane, but they could not accurately localize all objects. We found two participants (T3, T6) pointed out the accurate locations of all three objects, another two participants (T4, T5) pointed out the locations of two objects, and the rest (T1, T6) only pointed out the location of one object.

Effectiveness of Object Recognition

In the object recognition task, within three virtual objects, all six participants could recognize the virtual cabinet and estimate the rough dimension and the texture. As they described it as "tall" and "large". T3 also described the virtual cabinet as a "tall rectangular cabinet". T1 said the auditory and vibrotactile feedback was convincing to identify the cabinet.

Three participants (T2, T3, T4) could recognize the virtual table. Two participants (T1, T6) could describe the materials of the virtual table but could not identify it as a table. T5 found it difficult to tell the different feedback between the virtual chair and table.

Auditory feedback

Participants found the auditory feedback is significant to distinguish the materials of objects in virtual environment. For example, all participants could recognize the virtual cabinet using 3D auditory feedback, the auditory feedback from interacting with virtual cabinet was "real and easy to recognize". However, some participants experienced difficulty distinguishing auditory feedback between different objects in virtual environment, which resulted in trouble recognizing corresponding virtual objects. For example, T5 could not distinguish the auditory difference between the chair and the table, so she took a long time to identify the chair. As she mentioned, "The sounds are very similar."

Vibrotactile feedback

Most participants found the vibrotactile feedback is useful to perceive texture and size. T2 used the vibrotactile feedback to identify the height of the cabinet as he said, "The feedback keeps telling me to move (the virtual cane) upwards, and the sound is easy to tell, so I know it is a tall cabinet". Some participants even noticed the different vibrotactile feedback when they changed the cane strategies. For example, T3 said, "When I swept the virtual cane horizontally then I heard and felt vibration feedback, it made me feel that I was sweeping on a surface."

Exploration of Virtual World

Three participants could understand the size of the virtual world using MR Cane. All of them could describe the components of the virtual world including the walls, the number of objects and locations of them. For example, T2 said the virtual environment had a larger size than his dining room as he could not reach to one side of the wall. Some participants also found the cane strategies were practical to explore the virtual world. As T3 mentioned, "If I didn't learn the cane strategies, I would not know how to use the (virtual) cane in the virtual environment to interact with the objects."

5.3 Discussion

Our evaluation demonstrated that sighted participants were able to find all virtual objects, recognize some virtual objects and identify their locations in a virtual environment with the MR Cane. Our study also confirmed the feasibility of mobile VR exploration with the simulation of long cane and cane strategies.

In the experiment, ARKit successfully tracks iPhone's poses and we found the camera trajectories were smooth and no noticeable drift was found in the experiments. In addition, we've tested the user's head tracking algorithm and it provides reasonable estimation when users utilize two-point touch and constant touch in the experiment, thus help them to identify locations of some virtual objects during the VR exploration. We observed that all participants found all virtual objects, but they failed to localize some of the objects and to identify their types. It might be because our participants have not done a formal O&M training and lacked the basic skill to accurately construct their spatial mental models.

Although the testing result and user interviews with blind-folded users demonstrate some effectiveness of the proposed approach, we found the following limitations.

The first limitation is the fact that the user's movement of the MR Cane was not able to be restrained in our current implementation. As a result, in most cases, the MR Cane penetrated into virtual objects, namely the floor and the walls, taking away from the experience and causing confusion to users. In addition, vibrotactile feedback from the phone was directionless, making it difficult to apply cane techniques that rely on dragging the cane's tip across the junction where a vertical surface and a horizontal surface meet or detecting changes in elevation. The second limitation is the head tracking. Unlike other simulated cane approaches that use additional trackers, a very simple solution was proposed in our current implementation to predict head's poses: We assumed BVI users do not spin their heads while exploring the VR environment, hence the approach was not able to correctly predict the head's poses when users spun their heads and 3D audio did not reflect the correct the location of a virtual object. The problem may be solved by adding the second phone or a wearable sensor on the BVI user's head.

The third limitation, probably the biggest one, is our user studies. Due to the pandemic, our current prototype cannot be evaluated with BVI users, and hence the features of MR Cane were not fully utilized and explored by them. Though the sighted participants were asked to complete a VR tutorial and introduced cane strategies before they started experiments, it's still very difficult for them to correctly make use of the MR Cane. The cane strategies are essential to recognize and localize the virtual objects. For example, T3, who spent 20 minutes on tutorial practices, had a better performance than other participants. To moving the research forward considering the COVID-19 situation, currently we are developing a remote testing features in our app, which allows the cane users, researchers or O&M instructors work collaboratively on the experiments but remotely. We hope we can conduct the user studies with BVI users over the designed remote platform. The current evaluation tool is for sighted users and is not accessible to the BVI users. We are looking into ideas proposed in [14], which is an effective evaluation tool – a VR game including virtual targets and hazards in environment, allowing BVI users to navigate in the VR environment, while collecting targets and avoiding hazards. The game-like platform allows BVI users to evaluate the effectiveness of spatial exploration using simulated cane.

In addition, the MR Cane can be improved in several aspects. Real-world environmental sounds should be added into the actual VR training and testing to mimic the reality world environments, hence enhance BVI users their real-world spatial learning experiences. The app can also directly inform BVI users the object types (chair/table/cabinet and so on) to enhance their cognitive learning experiences, instead of having the users to guess the object types from various feedback. This will be important if O&M training becomes the focus of the VR exploration.

6 CONCLUSION

In this paper, we proposed the Mixed Reality Cane (MR Cane), a mobile VR application to simulate long cane interactions on iPhone and enable BVI users to walk in real space while exploring a virtual world. The proposed MR Cane proves to have potential to provide a supplementary tool to explore and navigate virtual environments during O&M training. The goal of the MR Cane is to present BVI users a simple accessible platform to explore and interact with the virtual environment with a simulating long cane. As a future work, we plan to conduct a formal user study with a group of BVI participants to help us better understand the strength and weakness of the proposed MR Cane system and take what we learn from them in the refinement of the designs. For example, we would like to enhance vibrotactile feedback, and improve the interface to allow user to explore the shape and geometry of different parts of virtual objects, which can further enhance BVI users' immersive VR experience and the ability to recognize and understand various complicated virtual environments.

ACKNOWLEDGMENTS

This research is supported by the NSF Partnerships for Innovation (PFI) Program via Award No. IIP-1827505, ODNI via the Intelligence Community Center for Academic Excellence (IC CAE) at Rutgers University (#HHM402-19-1-0003 and #HHM402-18-1-0007), and a CUNY Research Scholars Grant.

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