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ORIGINAL ARTICLE

Interactive mixed reality white cane simulation for the training of the blind and the visually impaired

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Abstract This paper presents a mixed reality tool developed for the training of the visually impaired based on haptic and auditory feedback. The proposed approach focuses on the development of a highly interactive and extensible Haptic Mixed Reality training system that allows visually impaired to navigate into real size Virtual Reality environments. The system is based on the use of the CyberGrasp^{TM} haptic device. An efficient collision detection algorithm based on superquadrics is also integrated into the system so as to allow real time collision detection in complex environments. A set of evaluation tests is designed in order to identify the importance of haptic, auditory and multimodal feedback and to compare the MR cane against the existing Virtual Reality cane simulation system.

Keywords Mixed reality · Force feedback · Rehabilitation

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1 Introduction

Human perception combines information of various sensors, including visual, aural, haptic, olfactory, etc., in order to perceive the environment. Virtual Reality (VR) and Mixed Reality (MR) systems are generally based on the use of advanced displays in order to provide an immersive visual interface. However, VR and MR applications are not limited to visual feedback [1]. Audio feedback as well as haptic feedback can be used for the creation of immersive applications. These modalities are also suitable for the creation of applications for the blind and the visually impaired. Virtual reality applications aim to immerse the user into a virtual environment by providing artificial input to its interaction sensors (i.e. eyes, ears, hands, etc.). The visual and aural inputs are the most important factors in human–computer interaction (HCI). However, VR applications will remain far from being realistic without providing to the user the sense of touch. The use of haptics augments the standard audio-visual HCI by offering to the user an alternative way of interaction with the virtual environment.

Developing force feedback interfaces allow blind and visually impaired users to access not only two-dimensional (2D) graphic information, but also information presented in 3D virtual reality environments (VEs) [2]. It is anticipated that the latter will be the most widely accepted, natural form of information interchange in the near future [3].

Potential benefits from virtual environments can be found in applications concerning areas such as education, training, and communication of general ideas and concepts [4]. However technical trade-offs and limitations of the currently developed VR systems are related to the visual complexity of a virtual environment and its degree of interactivity [5, 6]. Hitherto, several research projects have been conducted to assist visually impaired to understand

3D objects, scientific data and mathematical functions, by using force feedback devices [7–11].

The HOMERE system presented in [12] is a multimodal system dedicated to visually impaired people to explore and navigate inside virtual environments. The system provides the user with different kinds of feedback when navigating inside a virtual world: a force feedback corresponding to the manipulation of a virtual blind cane, a thermal feedback corresponding to the simulation of a virtual sun, and an auditory feedback in spatialized conditions corresponding to the ambient atmosphere and specific events in the simulation. A visual feedback of the scene is also provided to enable sighted people to follow the navigation of the main user.

In [13] a haptic VR tool developed for the training of the visually impaired is presented. The proposed approach focuses on the development of a highly interactive and extensible Haptic Virtual Reality training system that allows visually impaired, to study and interact with various virtual objects in specially designed virtual environments, while allowing designers to produce and customize these configurations. The training scenarios include cane simulation, and other used for performing realistic navigation tasks.

The purpose of this paper is to develop a mixed reality cane simulation environment based on the existing VR cane simulation [13] application and to conduct tests with blind users in order to obtain measurable results and derive qualitative and quantitative conclusions on the added value of the mixed reality system. The CyberGrasp haptic device was selected, based on its commercial availability and maturity of technology. We developed a mixed reality environment for cane simulation and performed comparative tests with end users in order to identify the advantages of the mixed reality cane simulation. Moreover a novel superquadric-based collision detection algorithm was integrated and tested with the system.

The paper is organized as follows. Section 2 describes an overview of the cane simulation system, including a general flow chart and features available in both the VR and MR systems. Section 3 describes the existing VR cane simulation system and includes details of the hardware setup as well as information concerning the force feedback calculation. Section 4 describes the novel mixed reality cane simulation application. Section 5 describes the usability evaluation of the system. Finally, Section 6 draws the conclusions.

2 System overview

The proposed system comprises mainly a powerful personal computer running the MR/VR Cane software application and a haptic device along with its control units. A 3D position and orientation-tracking device with two position sensors is required for the navigation applications of the system. The application is connected to a data set of virtual objects, scenarios and training cases, especially designed for ease of use and for adding value in the procedure of navigation training for visually impaired persons. All software applications have been developed using Visual C++.

This chapter describes the hardware setup used for the cane simulation applications (both VR and MR) as well as the software components that compose the cane simulation platform.

2.1 Hardware setup

The hardware prototype consists of the CyberGrasp™ haptic device, a powerful workstation with specialized 3D graphics acceleration, input devices (primarily mouse and keyboard), output devices other than the haptic device and the wireless motion tracker (Fig. 1). The prototype handles both human-hand movement input and haptic force-feedback using Immersion's CyberGlove® and CyberGrasp™ haptic device [14]. Another important component of the cane simulation system is the motion tracking hardware and software, required for tracking the position and orientation of the hand of the user. The system prototype utilizes Ascension's MotionStar Wireless™ motion tracker to accomplish this task.

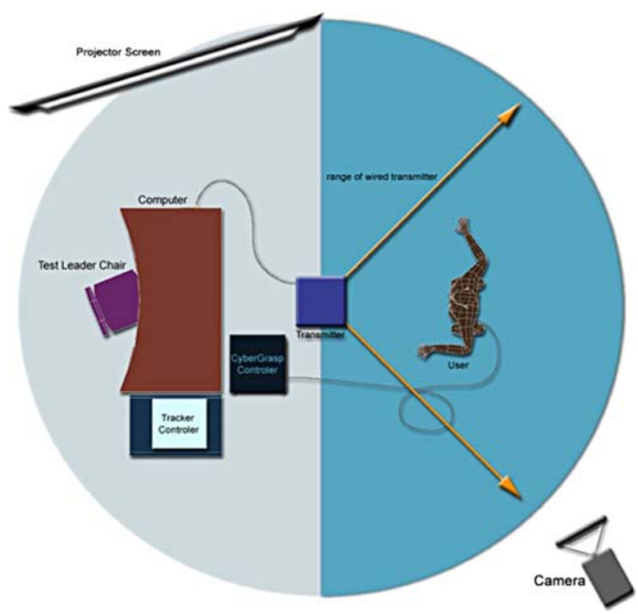

Fig. 1 Cane simulation setup

2.1.1 *Haptic device*

The prototype handles both human-hand movement input and haptic force-feedback using Immersion's CyberGlove® and CyberGrasp™ haptic devices [10]. CyberGlove® is a widely used human-hand motion-tracking device of proven quality. CyberGrasp™ is currently one of the very few force-feedback devices that are offered commercially, providing high quality of construction, operation and performance. The 350 g CyberGrasp™ exoskeleton is capable of applying a maximum of 12 N per finger force-feedback at interactive rates and with precise control.

Both devices are supported by the VHS™ software developer kit, which allows straightforward integration with custom VR software.

2.1.2 *Motion tracking*

An important component of the system is the motion tracking hardware and software, required for tracking the position and orientation of the hand of the user. The system prototype utilizes Ascension's MotionStar Wireless™ motion tracker to accomplish this task. Other motion trackers, offering similar or better accuracy and responsiveness and a similar way of communication via local network, can easily be plugged into the system.

The MotionStar Wireless™ Tracker system is a 6 *dof* measurement system that uses pulsed DC magnetic fields to simultaneously track the position and orientation of a flock of sensors. The specific motion tracking system has been proved to provide measurements of adequate accuracy and precision and also offers a considerably large workspace. On the downside, likewise to most magnetic motion trackers, metallic objects in its magnetic field and other magnetic field sources affect MotionStar™. However, with proper set-up of the tracked area and noise filtering algorithms, these inaccuracies can be reduced drastically.

2.2 Application core

The application consists of the following three main parts: (a) initialization part, (b) haptic loop and (c) visual loop. The initialization part establishes connection with the devices, reads the scene, initializes the collision detection algorithm [15] and starts the haptic and visual loops. The haptic loop updates the scene using data from the devices, checks for collisions between the hand and scene objects, sets the new position of the hand and objects, triggers feedback forces and enables sound playback. The visual loop reads the current position of scene objects and performs the scene rendering.

Figure 2 presents the general flow chart for the mixed reality cane simulation system. It is similar to the flow chart of the original VR application and includes the tracking of the real cane and a new module for force feedback calculation.

Collision detection is performed for collisions between the virtual cane and the VR scene using an SQ based collision detection algorithm presented in [16]. In order to check for collision between an object and a hand segment, the implicit formula of the superquadrics is calculated for each point of the object.

- If $F(x, y, z) > 1$; the point (x, y, z) lies outside the cane.
- Else the point (x, y, z) lies inside the cane.

Where $F(x, y, z)$ is the implicit formula of the superquadric that models the cane. If at least one point lies inside the cane collision is reported.

The cost of executing collision detection tests only for the vertices composing a 3D mesh, and not for the elementary surfaces as most traditional collision detection methods do, is that in cases, where the mesh is coarse and the triangles are relatively large, the superquadric may penetrate a triangle or even pass through it without collision report. In order to solve this problem additional control points are inserted inside each triangle so that the distance between adjacent points is constant, i.e. a 2D grid is applied onto the triangle. In this way the collision tests are performed for the control points for each segment of the virtual hand.

The system supports 3D sound using the OpenAL (http://www.openal.org) library in order to create realistic audio feedback.

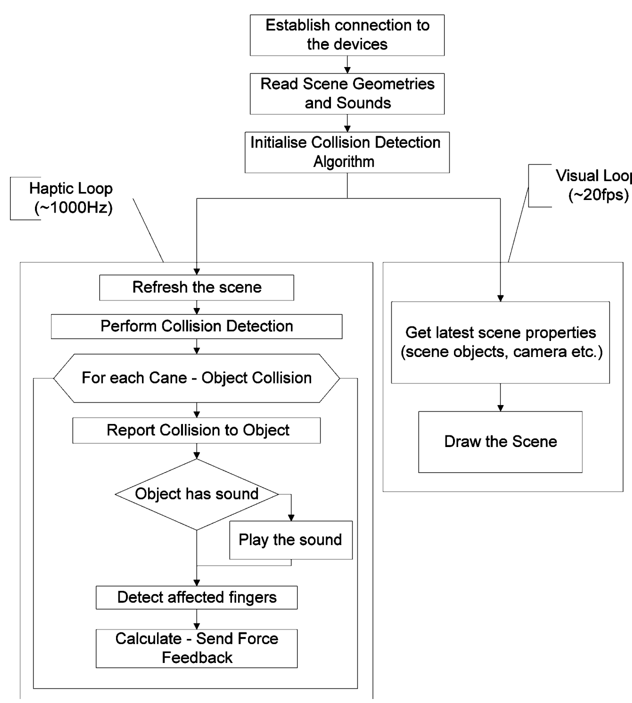

Fig. 2 General flow chart of the cane simulation environment

3 Virtual reality cane simulation

Cane simulation, has been implemented for realistic navigation tasks with the use of CyberGrasp™, which in combination with the Ascension MotionStar™ wireless tracker, led to a significant workspace expansion (up to 7 m). Cane simulation applications could include indoor and outdoor environments, such as navigation in the interior of a bank or a public building, traffic light crossing, etc.

The cane was designed to be an ''extension'' of the users' index finger. The force feedback applied to the users' hand, depends on the orientation of the cane relatively to the virtual object that it collides with. Specifically, when the cane hits the ground, force feedback is sent to the index finger of the user. Force feedback is applied to the thumb when the cane collides with an object laying on its right side and force feedback is applied to the middle ring and pinky finger simultaneously, when the cane collides with an object being on its left side.

Forces applied to the user can be summarized in: a constant continuous force that emulates the force provided by grasping a real cane, a cosine force effect (buzzing) applied to the user when the cane is penetrating an object and a jolt force effect is sent to the user when the cane hits an object or the ground.

The cosine force effect is described by the following equation:

$$F_{\mathrm{C}} = a\,(1 + \cos(2\pi\omega t)), \tag{1}$$

where a is the amplitude of the force.

The jolt force effect is given by the equation:

$$F_{\mathrm{J}} = d\,\mathrm{e}^{-kt^2} \tag{2}$$

where d is the amplitude of the force and k is the attenuation factor.

We have examined two different system configurations for simulating the force feedback for cane simulation.

In the first case, a two state force model was examined: (a) the cane does not collide with an object and (b) the cane collides with an object in the scene. The corresponding forces applied to the user are: (a) a constant continues force that emulates the force provided by grasping a real cane and (b) a higher-level constant force, applied to the user fingers when the cane collides with an object in the scene.

In the second case, a three state force model was examined: (a) the cane does not collide with any object, (b) the cane hits on an object in the scene, as illustrated in Fig. 3, and, (c) the cane is colliding continuously with an object in the scene (e.g. penetrates an object in the scene). The corresponding forces applied to the users are: (a) a constant continues force that emulates the force provided by grasping a real cane, (b) a jolt effect force and (c) buzzing.

Experimental evaluation has shown that in the first case the users had difficulties to distinguish the exact position of the object in the scene. The reason was that the users were feeling the same feedback when the cane was lying on the surface of an object, and when the cane was penetrating an object (due to which the system could not prevent the user from penetrating objects in the scene—note that the CyberGrasp™ is mounted on the users palm, i.e. not grounded). In the second case, however, the users could understand the position of the objects and navigate themselves in the scene, successfully.

In order to select the appropriate effect force for realistic simulation the following requirements have been taken into account: (a) the effect force used to warn the user that the cane is penetrating an object must be an effect that can be easily recognized and does not strain the fingers of the user when applied continuously, (b) the effect force that is applied to the user in order to feel that the cane hits an object, must apply the maximum force at the beginning and last for a short period of time.

The effect forces for each finger are generated using the following equation:

$$F = a\,(b + \cos(2\pi\omega t))\,(c + d\,\mathrm{e}^{-\zeta(t-\beta)^2}) \tag{3}$$

where F is the effect force, a is the amplitude coefficient, b and ω are the offset and the angular velocity for the cosine component, respectively, c is the offset for the exponential

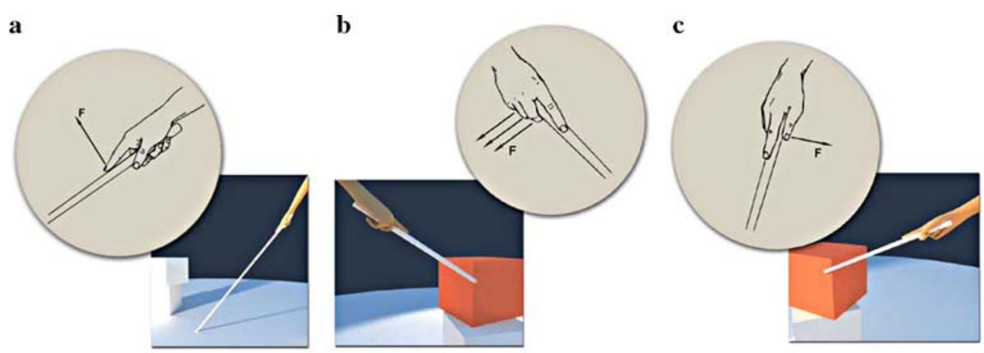

Fig. 3 Cane collision with the ground (**a**), an object on the left hand side of the user (**b**) and an object on the right hand side of the user (**c**)

component and d, ξ and β are the scale coefficient, the attenuation factor and the delay time for the exponential component, respectively.

Based on the above, the cosine force effect is selected to warn the user that the cane is penetrating an object, because it is an effect that does not strain the fingers of the user when applied continuously and also it is not similar to any realistic force that might be perceived by the cane. Thus, the user can distinguish that the cane is penetrating an object in the scene using only haptic information.

The jolt effect fulfills the characteristics of the effect force to be applied to the user when the cane hits an object. This effect is selected among other possible effects that fulfill these characteristics according to user's remarks in the pilot experiments.

In order for the test leader to be able to modify the simulation parameters online, based on the users requirements, the cane simulation application had to be adjustable in terms of the length of the virtual cane, the grasping forces (both the 'floor hit' force and the 'wall hit' force) and the buzzing level (force when cane is penetrating an object).

4 Mixed reality cane simulation

The fact that blind persons use different ways to grasp the cane, led to the decision of creating an application that can simulate various ways of grasping and manipulating the cane through the design of the MR cane simulation system. The MR interface is an extension of the VR cane simulation application. The user wears the CyberGrasp and a waistcoat for carrying the Force Control Unit (FCU) for the CyberGrasp and the Motionstar Control Unit to connect the magnetic sensors. The first sensor is attached to CyberGrasp device and the second sensor is attached to the real white cane (Fig. 4). Sound and haptic feedback are provided by the system upon the collision of the cane with the virtual objects with respect to their relative position. The parameters of the virtual cane (size, collision forces) are adjusted so that it fits to the real cane substitute and the user can perceive contact distances similarly as with the real one. Environmental sounds are assigned to static objects in the scene (e.g. realistic traffic lights sound is assigned to traffic lights in the virtual scene) as well as to dynamic objects (i.e. cars, bikes).

Force feedback calculation in the case of the MR application is more complex than in the VR case. There are a number of differences concerning calculation of force feedback: (a) the grasping force is deactivated in the MR cane simulation since the user grasps the real cane substitute, (b) The VR cane uses three distinct force feedback models while in the MR cane simulation force feedback is calculated dynamically.

Fig. 4 Testing the system in the laboratory

As already mentioned, CyberGrasp cannot provide force feedback to the arm of the user. This does not allow us to provide a feedback in order to neutralize the weight of CyberGrasp. To reduce the effort of the user the system allows tuning the force feedback using a constant value F_C. Forces calculated by the dynamics model described in the sequel are reduced by F_C.

A simplified dynamics model is used to calculate the force feedback applied to the fingers. The proposed model takes into account that CyberGrasp can apply forces approximately perpendicular to the user's fingertips. In order to detect fingers that should perceive force, the relative position of the user's digits and the cane is calculated along side with the moving direction of the cane. The effective force that (Fig. 5) is sensed by the user is calculated through

$$F_{eff} = F \cos(\theta) \tag{4}$$

where θ is the angle between the actual force F and the vector perpendicular to the fingertip.

Calculation of the force feedback is done in two steps. The first step calculates the relative position of the real cane and the human hand. The tracker sensor attached to a specific distance from the top tip of the cane as shown in Fig. 6.

To calculate its actual position and orientation both the distance from the top (d) and the radius (r) from the center of the cane to the tracker sensor has to be taken into account. Transformation received from the tracker is then modified so as to calculate the actual position of the white cane in global coordinates. Lets assume, without loss of the generality, that when the sensor resides on the coordinate center with zero rotation the cane resides on position $v = (x, y, z)$ with zero rotation. Then, to calculate the position and orientation of the cane in the world when the

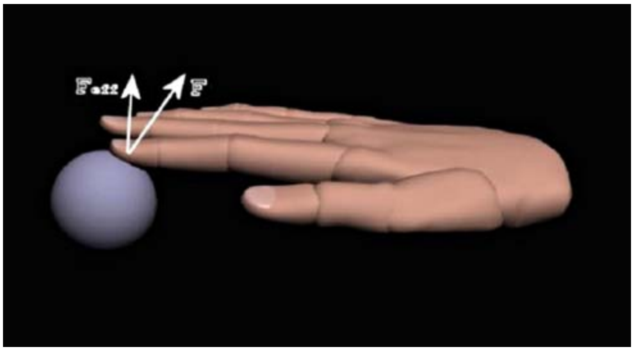

Fig. 5 Force feedback for the CyberGrasp

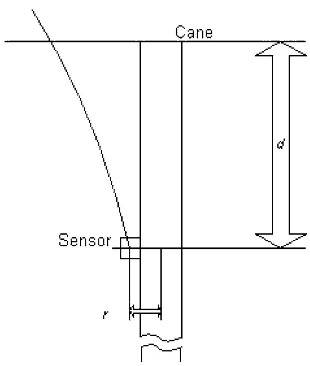

Fig. 6 Cane and tracker sensor

sensor resides on position (*X*, *Y*, *Z*) with an orientation defined by a rotation matrix *R* we need to use the following calculations:

$$v_{\text{cane}} = v_{\text{tracker}} + R\ v \tag{5}$$

where v_{tracker} is the position received from the tracker, v_{cane} is the actual position of the cane and the rotation matrix of the cane is *R*.

Position of the hand is calculated in a similar way using the offset between the sensor and the palm joint of the human hand.

$$v_{\text{hand}} = v_{2\text{tracker}} + R_2\ v \tag{6}$$

where $v_{2\text{tracker}}$ is the position received from the second tracker sensor, v_{hand} is the actual position of the palm and R_2 is the rotation matrix of the palm.

Furthermore, in the case of human hand the finger joint angles are measured using the CyberGlove so as to have the proper posture of the human hand. The calculations result in having the global position and orientation of the hand and the cane and thus allow calculating their relative position.

The second step is to calculate the force feedback to be applied on the human hand. This is performed whenever the white cane collides with a scene object. The force applied to the human's hand is in the direction of the normal of the surface at the collision point. Let's assume that the cane hits an object that resides in half space A (Fig. 7). Force feedback is provided only to the finger of half-space B that satisfies the following conditions:

- It collides with the cane.
- It is the closest finger to the collision point among all colliding fingers on B.

The conditions for the fingers of half-space A (secondary feedback fingers) are:

- The finger collides with the cane.
- It lies further from the collision point than the main-feedback finger.

It is obvious that the secondary feedback fingers receive force feedback in the opposite direction of the normal.

Due to the fact that CyberGrasp cannot prevent the user from penetrating the virtual objects with the real cane, the amplitude of the force is not calculated dynamically, but is assumed constant concerning the preferences of the user. The Jolt effect is used, as in the case of virtual cane. Furthermore, forces that can be applied are perpendicular to the user's fingertips. The force amplitude send to CyberGrasp is calculated using Eqs. (1) and (4) or (2) and (4).

The main advantage of the MR cane simulation over the VR system is that the user can handle the cane as in real world conditions without any restrictions in terms of grasping. This cannot be implemented in the VR system because grasping an object (i.e. the cane) in the desired way without using any visual feedback is a difficult task and could cause inconsistence between the actual position of the VR cane and the actual position of the user's hand.

5 Usability evaluation

Initial versions of the applications have been evaluated with blind and visually impaired users. Specifically, the white cane simulation has been tested with blind and visually impaired users from the Thessaloniki Blind School and the Pan-Hellenic Blind association.

Twenty-six persons participated in the tests from the Thessaloniki Local Union of the Panhellenic Association for the Blind in Greece. The users were selected so as to represent the following groups: blind from birth, blind at a later age, adults, and children. The evaluation consisted of three phases. In the first phase the users were introduced to the system and were allowed to use it for a while in order to get used to the device and to calculate the most

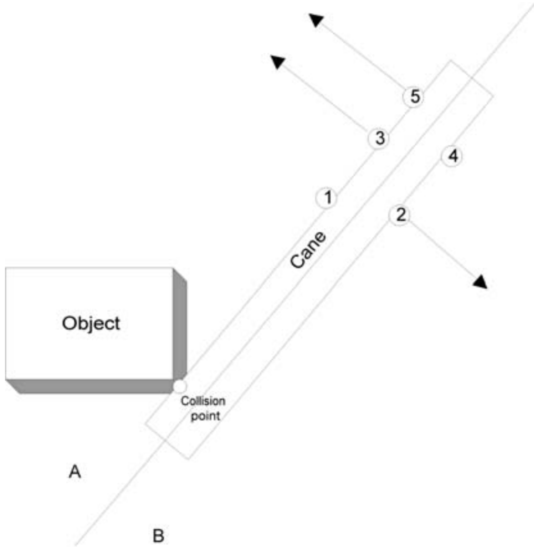

Fig. 7 Force applied to the fingers

comfortable parameters for the cane (i.e. length, force amplitude).

In the second phase they performed the task. The user is asked to cross a traffic light crossing using a virtual cane. The user is standing at the beginning of the test room wearing the CyberGrasp^{TM} and a waistcoat for carrying the FCU for the CyberGrasp^{TM}. When the test starts, the user is asked to grasp the virtual cane or the real cane substitute. The parameters of the virtual cane (size, grasping forces, and collision forces) are adjusted so that the user feels that it is similar to the real one. After grasping the cane, the user is informed that he/she is standing in the corner of a pavement (shown in Fig. 6). There are two perpendicular streets, one on his/her left side and the other in his/her front. Then, he/she is asked to cross the street in front of him/her.

The user should walk ahead and find the traffic light located at about one meter on his/her left side. A realistic 3D sound is attached to the traffic light informing the user about the condition of the light. The user should wait close to it until the sound informs him/her to cross the street passage (green traffic light for pedestrians). When the traffic lights turn to green the user must cross the two meters wide passage until he/she finds the pavement at the other side of the street. It is also desirable that the user finds the traffic light at the other side of the street.

The total times to complete the task, user's comments and success or failure in performing the task were recorded for each user. In the third face they answered a questionnaire, about the performance and the usability of the system.

According to their comments during the tests and their response to the questionnaires, the following conclusions can be drawn: It was deemed very important to utilize both acoustic and haptic feedback, as they are indispensable for the orientation. It is also important to note that a 96% of the users have characterized the tests as useful or very useful.

An initial comparative test has been performed to estimate the importance of using a mixed reality system over a VR system as well as the significance of each modality to users' navigation. Specifically, the system was evaluated for the following cases:

- MR with haptic feedback, without audio feedback (sound from the traffic lights)
- MR without haptic feedback, with audio feedback
- VR with multimodal feedback (both haptic and audio)
- MR with multimodal feedback.

The evaluation was based on psychophysical criteria and was performed using questionnaires. The results showed that the users preferred the MR simulation with multimodal feedback in terms of usability. The second choice was the VR with multimodal feedback. Third was the MR using only audio feedback and last was the MR using only haptic feedback. The ranking clearly illustrates the importance of the multimodal feedback.

In every case all the users managed to perform the tests successfully (i.e. all the users managed to cross the road while the traffic light was green). However for each case the users had differences in time required to find the second traffic light.

The average times to reach the second traffic light where 6.0, 6.5, 7.0 and 7.1 s for the multimodal MR Cane, multimodal VR Cane, Haptic MR Cane and audio MR Cane, respectively.

The ANOVA method was used to compare the performance of the users between the various test cases. The critical value for the parameter $F_{critical}$ of the ANOVA method was calculated to be equal to 4.03 (assuming probability equal to 0.05 and degrees of freedom between groups equal to 1 and within groups equal to 50). Comparing the results of the multimodal MR Cane and the multimodal VR Cane the value for F was 4.9, which is higher than the $F_{critical}$. On the other hand the F value comparing the mono-modal cases of the MR canes had the value of 0.21, which does not show any significant difference between the two cases.

6 Conclusions

The evaluation results on the initial version of the system were promising. The fact that blind persons use different ways to grasp the cane led to the decision of creating an application that can simulate various ways of grasping and manipulating the cane. This led to the design of the MR cane simulation system, which tracks the position of the users hand and the real white cane.

In the cases of the cane simulation, technical limitations constrain its applicability. Specifically, the system cannot prevent the user from penetrating objects in the virtual environment. The maximum workspace is limited to a 7 m—diameter hemisphere around the tracker transmitter (the 1 m limitation, caused by the CyberGrasp™ device is solved by using a backpack so that the user can carry the CyberGrasp™ actuator enclosure). The maximum force that can be applied is limited to 12 N per finger and the feedback update rate is 1 KHz.

Concluding, the usability evaluation results demonstrate that the proposed mixed reality application was considered as an improvement of the original work [13], whereas it still leaves a lot of room for improvement and supplement. Provided that further development is carried out, the system has the fundamental characteristics and capabilities to incorporate many requests of the users for the creation of a more realistic training environment.

The approach chosen, fully describes the belief of blind people to facilitate and improve training practices. It represents an improvement of life for the blind and the visually impaired people when connected to reality training. These facts are evident from the participants' statements.

Except from the direct benefits of the proposed system, as many of the users mentioned, the technology based on virtual environments can eventually provide new training and job opportunities to people with visual disabilities.

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