Design and Implementation of Haptic Virtual Environments for the Training of the Visually Impaired

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***Abstract*—This paper presents a haptic virtual reality (VR) tool developed for the training of the visually impaired. The proposed approach focuses on the development of a highly interactive and extensible haptic VR training system (the ENORASI VR 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. Based on the system prototype and the use of the CyberGrasp haptic device, a number of custom applications have been developed. An efficient collision detection algorithm is also introduced, by extending the proximity query package (PQP) algorithm to handle five points of contact (a case studied with the use of CyberGrasp). Two test categories were identified and corresponding tests were developed for each category. The training scenarios include: object recognition and manipulation and cane simulation, used for performing realistic navigation tasks. Twenty-six blind persons conducted the tests and the evaluation results have shown the degree of acceptance of the technology and the feasibility of the proposed approach.**

***Index Terms*—Haptics, training, visually impaired, virtual environments.**

I. Introduction

IN RECENT years, there has been a growing interest in developing force feedback interfaces that allow blind and visually impaired users to access not only two-dimensional (2-D) graphic information, but also information presented in three-dimensional (3-D) virtual-reality environments (VEs) [1]. It is anticipated that the latter will be the most widely accepted, natural form of information interchange in the near future [2].

The greatest potential benefits from virtual environments can be found in applications concerning areas such as education, training, and communication of general ideas and concepts [3]. The technical tradeoffs and limitations of the currently developed virtual reality (VR) systems are related to the visual complexity of a virtual environment and its degree of interactivity [4], [5]. Hitherto, several research projects have been conducted to assist visually impaired to understand 3-D objects, scientific data, and mathematical functions, by using force feedback devices [6]–[10].

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Researchers at Stanford University work on the research field of bringing the domestic computer world to people with disabilities. The result is an interface (Moose, [11]) that supports blind people in using the MS Windows operating system. Nowadays, their research is focused on modifying Moose's interface for its use in Internet navigators.

A considerably affordable mouse with force feedback is FEELit, produced by Immersion Corp.[1] Although the cost of the device is low, it has a restricted area of use, mainly due to its low-bandwidth force feedback. Nowadays, research groups typically make use of PHANToM (Sensable Technologies Inc., Woburn, MA) [12], [13] and/or the CyberGrasp data glove (Immersion Corporation).

PHANToM is the most commonly used force feedback device; it is regarded as one of the best on the market. Due its hardware design, only one point of contact at a time is supported. This is very different from the way that we usually interact with surroundings and thus, the amount of information that can be transmitted through this haptic channel at a given time is very limited. However, research has shown that this form of exploration, although time consuming, allows users to recognize simple 3-D objects. The PHANToM device has the advantage to provide the sense of touch along with the feeling of force feedback at the fingertip. Its main disadvantage is broad when identifying small objects. In these cases, people tend to use both their hands and all their fingers; it is proven that object identification with only one finger is difficult [14]. Many research groups study methods of texture and geometry refinement in order to improve the sense of touch for texture [15], [16] and surface curvature [17] identification when using PHANToM.

The advent of Logitech WingMan force feedback mouse has given researchers an alternative. The WingMan mouse has drawn a lot of attention in the research field and several research projects have been conducted to apply this device for the support of visually impaired in virtual environments [18]–[20].

CyberGrasp is another haptic device with force feedback rapidly incorporated to research lines. A research group working with CyberGrasp is led by Sukhatme and Hespanha at the University of Southern California. They focus on helping blind children to learn words, sounds and object forms, through this force feedback data glove [21]. Others include Schettino, Adamovich, and Poizner, researchers in the Rutgers University,

[1] Immersion Corporation, Los Angeles, CA, http://www.immersion.com/, 2002.

(a) (b)

Fig. 1. CyberGrasp haptic device attached to the hand of a user.

Newark, NJ, working on a project, which deals with the ability of people to adjust their hands and fingers to object forms that they have seen before [22].

The proposed paper focuses on the development of a highly interactive and extensible haptic VR training system (the ENORASI VR training system) that allows visually impaired people to study and interact with various virtual objects in specially designed virtual environment configurations. This paper also outlines the VR applications developed for the feasibility study (FS) tests, carried out in the Informatics and Telematics Institute in Greece for the Information Society Technologies (IST) European project ENORASI. The main goal of this paper is to develop a complete training system for the blind and visually impaired, based on techniques for haptic interaction in simulated VR environments [3], [17]. The challenging aspect of the proposed VR system is that of addressing realistic virtual representation without any visual information.

More specifically, the main objective of this work is to develop specialized VR setups and to conduct extensive tests with blind users in order to obtain measurable results and derive qualitative and quantitative conclusions on the added value of an integrated system aiming to train the visually impaired with the use of VR. The CyberGrasp haptic device (shown in Fig. 1) was selected, based on its commercial availability and maturity of technology. A number of custom applications (the feasibility study tests) has been developed utilizing a new optimized collision detection algorithm (based on PQP [23]) specially designed for the CyberGrasp haptic device, in order to improve the performance of the whole system. Earlier versions of the proposed work have been presented in [24], [25].

The advantages of the proposed method over existing VR methods are the improvements this approach offers in terms of usability and accessibility in applications such as training of the blind and the visually impaired using VR. These advantages can be summarized by:

1) providing the ability to use virtual training environments for the blind with large workspaces (up to 7–m-diameter hemisphere);
2) the support of more natural user interaction with the virtual environments (using all the fingers and not just one point of contact);
3) the incorporation of the novel cane simulation system (to our knowledge, this paper presents the first system supporting cane simulation in virtual environments for the training of visually impaired).

Additionally, the proposed system uses the modified collision detection algorithms that can reduce collision detection time up to around 50% (for applications utilizing all five points of contact with the virtual object).

Technical advances like larger workspace and five-finger interaction expand the state space of interaction. Although there do exist applications in other research areas (mechanical, simulation, visualization, and surgical) using large-space workspaces and others that utilize five-finger interaction in virtual environments, no applications exist in making use of this technology in producing accessible environments for the visually impaired. Most applications focusing in assisting people of this group are limited to single finger interaction and, in general, are desktop constrained applications. Concerning cane simulation, the use of grounded haptic devices has limited the application areas of VR for the training of visually impaired. The use of the CyberGrasp haptic device and the development of fast collision detection suited for the applications, made cane simulation applications possible.

The paper is organized as follows. Section II presents the architecture of the proposed system and analyses the main components of the ENORASI prototype, i.e., the scenario-authoring tool, the new collision detection algorithms and the simulation system, i.e., the ENORASI prototype. Section III, describes in detail the feasibility study tests performed, while Section IV presents the feasibility study evaluation results. Finally, conclusions are drawn in Section V.

II. System Prototype Development

The proposed system comprises mainly a powerful personal computer running the ENORASI software application and a haptic device along with its control units. The detailed architecture of the ENORASI system and its interface components with the user and the data is presented in Fig. 2. The 3-D position and orientation-tracking device is optional for the navigation applications of the ENORASI training system. The ENORASI

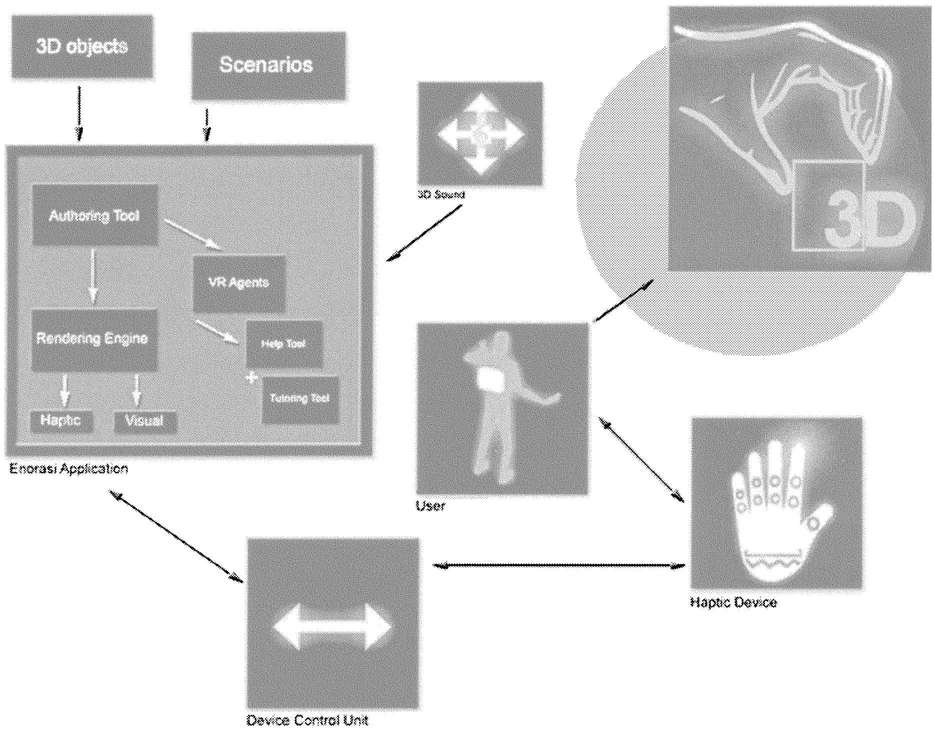


Fig. 2. ENORASI system architecture and its interface components with the user and the data.

software application includes an authoring environment for developing scenarios and training cases, the haptic and visual rendering modules (visual rendering is needed for monitoring the performance of haptic rendering) and the intelligent agents which implement the guidance and help tools of the system. The ENORASI software application is connected to a database of virtual objects, scenarios, and training cases, especially designed for ease of use and for adding value in the procedure of training visually impaired persons. All software applications have been developed using Visual C++.

A. ENORASI Hardware Prototype

The ENORASI hardware prototype consists of the CyberGrasp haptic device, a powerful workstation with specialized 3-D graphics acceleration, input devices (primarily mouse and keyboard), output devices other than the haptic device and the wireless motion tracker (primarily speakers and if necessary a Braille display).

1) Haptic Device: The ENORASI prototype handles both human-hand movement input and haptic force-feedback using Immersion's CyberGlove and CyberGrasp haptic devices [9]. 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 [26] software developer kit, which allows straightforward integration with custom VR software.

2) Motion Tracking: An important component of the ENORASI training 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 [27] 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 six-degree-of-freedom 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 setup of the tracked area and noise filtering algorithms, these inaccuracies can be reduced drastically.

B. ENORASI Software Prototype

The ENORASI software system consists of the scenario authoring application, the core ENORASI interactive application, drivers for the haptic device and a 3-D modeling system for the creation of the virtual environments. The 3-D Studio Max modeling tool, release 3.1, by Kinetix Autodesk Inc., Los Angeles, CA, was used for the design of the virtual environments.

The ENORASI software prototype shown in Fig. 3, supports both authoring and simulation functions. A user can use the prototype to import VR modeling language (VRML) format objects, place them in a new or existing scene, set their properties,

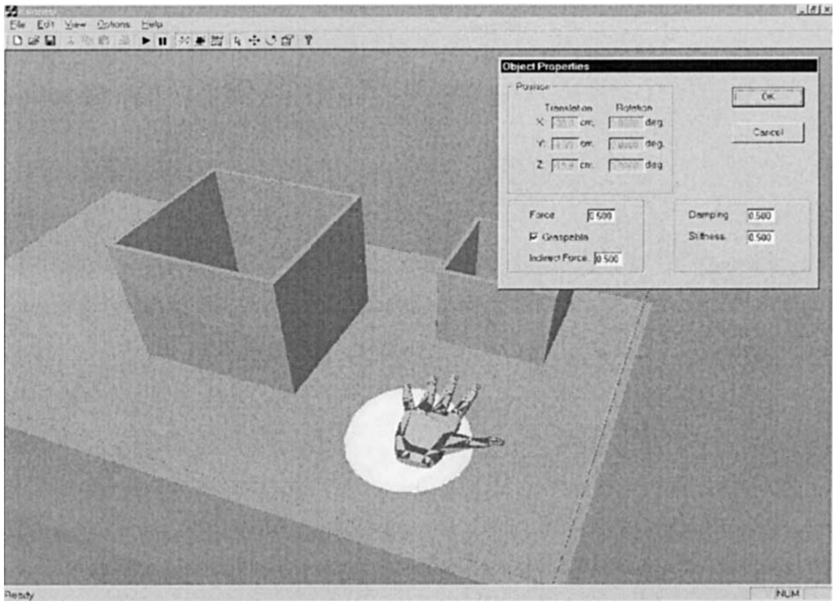


Fig. 3. ENORASI software prototype snapshot.

and navigate through the scene by starting the simulation. The edited scene can be saved for later use.

In general, the ENORASI software prototype has the following features.

1) *Open hardware architecture:* Supports the use and full control of more than one force feedback haptic devices simultaneously.
2) *Authoring capabilities:* Empowers designers by providing an authoring environment for designing virtual environments optimized for the blind.
3) *Evaluation and assistive tools:* Provides visual output to be used by the (sighted) training test leader and 3-D environmental sound support for both the user and the trainer.
4) *Technical enhancements:* Supports multiple collision detection algorithms (Rapid, PQP, V-CLIP, SOLID).
5) *Direct scene configuration:* Supports the modification of object haptic properties (stiffness, dumping, graspable/nongraspable, etc.) as well as operations such as translation, rotation, and scaling. Scaling, in particular, can be used to interactively decrease the size of the object to be examined (i.e., an aircraft or a building), in order to allow the user to get an overview of it and interact with it dynamically. The object can then be scaled back to the real size, to allow realistic investigation of the details.

All applications developed using the ENORASI software prototype consist of the following three main parts: 1) the initialization part; 2) the haptic loop; and 3) the visual loop which constitute the main operation loop of the proposed system (Fig. 4).

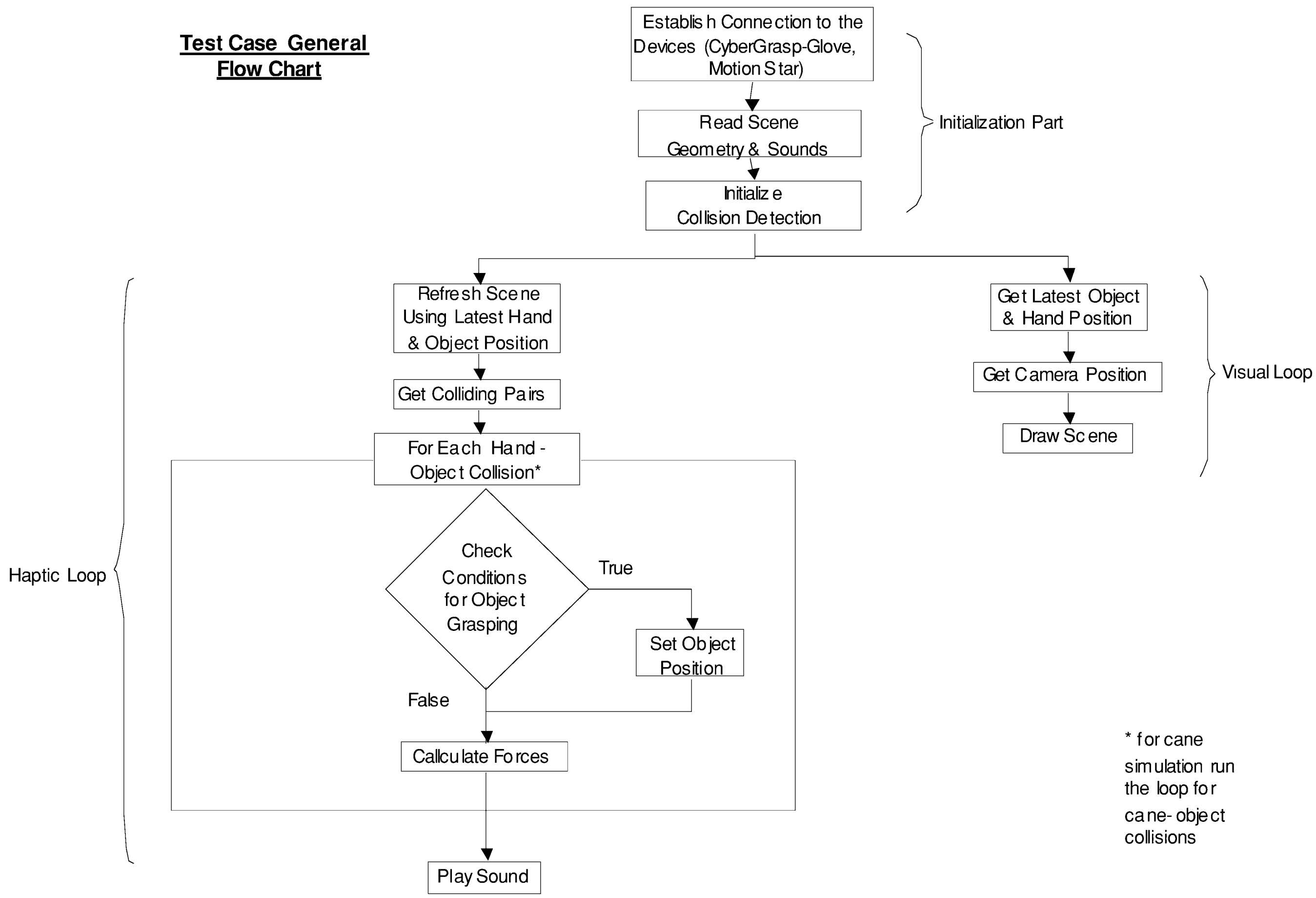
The initialization part of the prototype establishes connection to the devices (CyberGrasp-Glove, MotionStar Tracker), reads the scene (models and sounds), initializes the collision detection algorithm, and starts the haptic and visual loops.

The haptic loop updates the scene using data from the devices, checks for collisions between hand and scene objects, checks conditions for object grasping, sets the new position of any translated object, and sends feedback forces and sounds to the user. There are two input devices, the glove and the motion tracker, and one output device, CyberGrasp. This device, which provides the force feedback, runs its own control loop (on the device control unit) on 1 KHz [28]. The update rate of the motion tracker is 100 Hz and the update rate of the 22-sensor CyberGlove connected at 115.2 Kb is close to 250 Hz. In order to update feedback data to the CyberGrasp device using 1 KHz, we calculate intermediate position values for the motion tracker and the fingers using linear interpolation. The position values are then sent to the collision detection algorithm and feedback forces are calculated and transmitted to the CyberGrasp device. Collision detection is performed only for the fingertips. Collision detection is performed using the proposed H-PQP algorithm, which in many cases reduces the total collision time up to 50%. The system needs to have at least two input values from each device to calculate intermediate position values. The overall delay produced by the input devices equals to the delay caused by the device with the lowest update rate. Thus, the system has an overall delay of 10 ms due to the delay in receiving data from the tracker (100 Hz). Because of this overall delay and in order to perceive realistic haptic feedback, users were asked to move relatively slow when interacting with the system.

Correspondingly, the visual loop gets as input the latest camera, hand, and scene object positions and draws the scene. The update rate is approximately 20 Hz (20 frames/s).

C. Hand Model

The locations of the fingers were computed using the VHS Library [26]. Initially, a skeleton structure of the hand is designed internally (Fig. 5). Then, raw data received from the CyberGrasp glove are translated to rotations of the skeleton joints. Each finger, including the thumb, consists of three joints: the



consists of the initialization part, the haptic and the visual loop.

Fig. 4. General flowchart of the ENORASI prototype applications. The main application loop consists of the initialization part, the haptic, and the visual loop.

inner, the proximal, and the distal joint. Fig. 5, presents the joints and the corresponding degrees of freedom (DOF) for each joint.

The inner joint of the thumb has two DOF and thus it can be rotated around axis A, that is approximately parallel to the line connecting the wrist joint and the inner joint of the middle finger, and axis B, which is perpendicular to the plane defined by the axis A and the line connecting the inner and proximal joints of the thumb. Fig. 5, presents the rotation axis of each joint of the thumb and index fingers. The middle, ring, and pinky fingers have the same structure as the index finger.

The palm joint is located to a position, which is relative to the position of the tracker sensor, which resides on the top of the CyberGrasp device. The transformation used to compute the position of the palm joint in relevance to the tracker sensor position is initially computed for each user during the calibration phase.

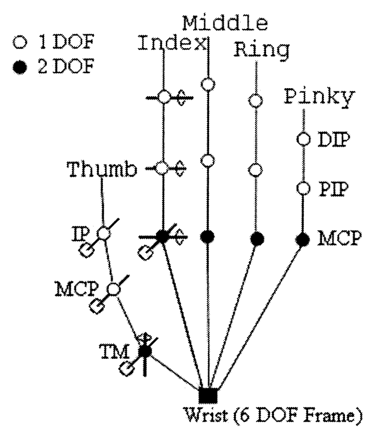


Fig. 5. Hand animation model.

The CyberGlove is calibrated for each user, using the default procedure provided by the manufacturer [26]. Each user was asked to make a couple of predefined gestures and the software automatically computed the offset and the gain of the sensors. The calibration procedure consisted of two steps: the default calibration step and the accuracy enhancement step. The default calibration automatically computes the calibration parameters based on the input provided by the user performing some simple gestures for a certain period of time. The accuracy enhancement step requires that the users perform a number of specific more complex gestures defined in [26]. In the following, the administrator of the tests corrects manually the calibration parameters, if needed, using the VHS calibration software. The CyberGrasp is also calibrated using the procedure described in [26]. According to the CyberGlove specifications, the sensor resolution is 0.5° and the sensor repeatability is 1°.

D. Collision Detection

Collision detection is a core part of the control system that ensures smooth, effective, and precise synchronization between the artificial digital world and the haptic hardware device. In the feasibility study applications, we have evaluated the Rapid [29] and the PQP [23] collision detection algorithms. In Rapid, hierarchical representation is based on oriented bounding box (OBB)-trees. This algorithm is applicable to all general polygonal and curved models. It precomputes a hierarchical representation of the models using tight fitting oriented bounding box trees. It can accurately detect all the contacts between large complex geometries composed of hundreds of thousands of polygons, being at the same time sufficiently fast for most VR applications. PQP is an algorithm performing three types of proximity queries on a pair of geometric models composed of triangles: 1) collision detection; 2) separation distance computation; and 3) approximate distance computation [23].

It was concluded that PQP is more suitable for use with the CyberGrasp, which works significantly better when distance information is available. A customized version of that algorithm was developed to optimize the performance of the system.

1) PQP Algorithm: PQP [23] is a fast and robust general proximity query algorithm, which can be used for exact collision detection between 3-D objects. The algorithm is capable of detecting collisions between convex and concave objects.

In PQP, a swept sphere volume is used as the bounding volume (BV). A BV is the geometry defined to bound sets of geometric primitives, such as triangles, polygons, etc. The BVs at the nodes of a bounding volume hierarchy (BVH) belong to a family of three different swept sphere volumes. They correspond to a sphere, and more complex volumes obtained by sweeping along either an arbitrarily oriented line or along an arbitrarily oriented rectangle.

In the case of hand–object collision, the case described in the present paper, one of the objects is always known *a priori* (the hand part, i.e., the fingertip). The fingertip is a convex 3-D geometry. However, we have no clues for the second object. In order to optimize collision detection in applications utilizing the CyberGrasp haptic device (that has five points of contact), we have proposed to modify the method used in PQP to parse the tree structure created during the initialization of the 3-D objects. This has led to two extensions of the PQP algorithm, namely subtree selective PQP (SS-PQP) and hand-based PQP (H-PQP), which are described in detail in the following subsections.

2) SS-PQP: In this paper, we propose the integration of a subtree selection algorithm to the PQP, so that the recursive steps of the main algorithm will compare only a subset of the BV pairs in the hierarchy tree.

First, the center of mass is calculated for each part of the hand geometry (e.g., fingertip). The center of mass is used during the traversing of the BVH tree in order to skip BV tests in a more efficient way. The projection of the center of mass on the splitting axis is compared to the splitting coordinates [23] and the BV that lies on the same side with the center of mass is examined for potential overlapping according to inequality (1)

$$|\mathbf{c} - \mathbf{p}| > d \tag{1}$$

where $\mathbf{c}$ is the splitting coordinate vector, $\mathbf{p}$ is the projection of the center of the mass on the separating axis, and d is the distance threshold. The distance threshold is chosen to be equal to the bounding sphere radius of the second object. When (1) is true, only one of the child BVs is examined further for possible collision. The other BV is tested only when the distance between the splitting coordinates and the projection of the center of mass is less than a threshold, depending on the size of the geometry of the BV that belongs to the hand part. In this way, more computations have to be performed before a specific BV test, but the number of BV tests is reduced, which results to a valuable reduction of the average time needed for collision detection between the hand and the object.

3) H-PQP: In SS-PQP, the geometry of each part of the hand was tested individually for collision. In H-PQP, the palm and the fingers of the hand are assumed as one single geometry and collision detection is initiated using a bounding volume of the whole hand (in any possible posture) as the test geometry. The hand BV hierarchy is not a regular BV hierarchy. A regular BVH consists of two children, which have a constant transform in relation to the BV transform. The hand BVH contains five children nodes (the five finger tips), and each of the nodes can be in a variety of relative positions. As long as the BV of the tested object (or subobject) is larger than the BV of the hand, the object BV hierarchy is traversed. When the BV of the object (subobject) is smaller than the BV of the hand, the hand splits into the five BVs that correspond to the five fingertips. In this case, the relative transforms between fingertips and the subobject have to be recalculated and the algorithm reduces to the PQP or the SS-PQP algorithm. This approach improves the results when collision detection is between hand and relatively large objects. However, it may decrease the performance of the proposed algorithm when the hand collides with small objects. The fact that the algorithm reduces to SS-PQP explains also the fact that there is no improvement in the number of triangle tests with the use of H-PQP (all triangle tests performed in the SS-PQP are still performed with the H-PQP-gains are expected in the BV tests), as shown experimentally in Table I.

The proposed extensions of the PQP algorithm, namely SS-PQP and H-PQP, were compared to PQP in terms of performance in the collision of the hand with a sphere and a spring, each one consisting of 7826 and 7306 triangles, respectively. In all tests, the fingers of the hand were closing, using a constant angle step for each joint on the finger. The tests started from the same hand position and finished when all the fingers were in touch with the object. The position of the object remained constant during the tests. The large-sphere and large-spring tests used the same geometries scaled by 10. Total times value reported in Table I, are average values of 30 measurements for each test. As seen in Table I, reduction of total collision time may range from 1% to 47% depending on the geometry and the relative position of the object colliding with the hand.

E. Scenario-Authoring System

The term "scenario" is used to describe the set of data required to describe and simulate a virtual world. The ENORASI scenario-authoring system is composed of two components: 1) the main scenario-authoring tool that is used to develop a

TABLE I
COMPARISON BETWEEN PQP AND THE PROPOSED SS-PQP AND H-PQP EXTENSIONS

Test	Total Number of BV tests			Total Number of Triangle tests		Average time per collision test (msec)		
	PQP	SS-PQP	H-PQP	PQP	SS-PQP & H-PQP	PQP	SS-PQP	H-PQP
Hand - sphere	631036	511082	505637	38106	32125	2.77	2.73	2.73
Hand -Large sphere	237702	158222	149261	26112	18725	1.17	0.95	0.92
Hand - Spring	1784789	1349884	1349033	94136	70153	7.585	7.11	7.10
Hand - L. Spring	311225	130285	115032	22644	10132	1.33	0.71	0.68

scenario and to design a virtual world consisted of objects with geometrical properties; and 2) the training case authoring tool, which is based on existing scenarios. In order to support this, two data structures have been developed: the *scenario data structure* and the *training cases data structure*.

The *scenario data structure* contains information about objects (shape, properties), hierarchy, environment, textual, and sound information about elements contained in the virtual world. The *training case data structure* contains information about training case scenarios, tasks to be performed, guidance/tutoring and help, additional information like introduction to training case, guidelines for the assessment of the degree of achievement of training objectives, etc.

The scenario files are in XML format and contain for each scene object parameters such as: initial position and orientation, object stiffness and damping, direct force intensity, the graspable/nongraspable property, the force to be applied to the user when a grasped object collides with another object in the scene, the sound played when the user touches an object, the sound played when a grasped object collides with another object in the scene and finally the collision detection algorithm to be used for each particular scenario.

The test cases developed in this paper (described in detail in the following sections) have been designed using this scenario data structure. Each training case referred to a separate *training case data structure* where special properties for the objects (e.g., animation) and training cases objectives were described.

III. FEASIBILITY STUDY TESTS

Twenty-six persons from the Local Union of Central Macedonia of the Panhellenic Association for the Blind, Greece, have participated in the tests. The users were selected so as to represent the following groups: blind from birth, blind at a later age, adults, and children.

The 26 participants (14 male and 12 female) went through the feasibility study tests program. The average age was 32.8 years—the youngest participants were 19 years old and the oldest 65 years old. Forty-two percent of the participants were blind from birth, 14.3% went blind before school age (1–5 years of age), 23.4% during schooldays (6 to 17 years), and 16.3% after school time or late youth (17 to 25 years). Also, 40% of the persons tested were students, 28% telephone operators, 12% unemployed, 6% teachers, and 2% professors, librarians, educational coordinators, and computer technicians. Finally, 38% of them knew about haptics and 24% had used a similar program.

The expectations of the users from the program were identified as follows: "recognize shapes of objects," "have access to the 3-D object," "feel details of objects," "vibration outlines," "explore objects," and "play a new game. " Some of the participants did not reply at all, others did not have any idea what to expect from the program.

The users were introduced to the hardware and software a day before participating in the tests. The introductory training, took approximately 1 h per user. The majority of them had no particular problems when interacting with the system. The motivations for this pretest was to introduce the users to a technology completely unknown to them, while ensuring that they feel comfortable with the environment of the laboratory. The pretest consisted of simple shape recognition tasks, manipulation of simple objects and navigation in the haptic virtual environment using cane simulation.

The main Feasibility Study tests took approximately 2 h per user, including pauses. The purpose of the feasibility study was not to test the reaction of a user to a haptic system. Rather, the idea was to try to obtain information about the use of such a system by a user who is somewhat familiar with the use of haptics. During the test procedure, the tasks were timed and the test leader was monitoring the performance of the users.

The tests were implemented by developing custom software applications based on the ENORASI prototype. Their parameters were tuned in two pilot tests performed in advance with visually impaired users. The final feasibility study tests were designed to include tests on tasks similar to that of the pilot tests, but with varying level of difficulty. For example, a test could consist of an easy task, a middle level task and a complicated task. The reason for this design approach was to use the results of the feasibility study in order to gather useful information for the design of the final system.

A. Feasibility Study Tests Design

From the ENORASI project user requirements analysis [30], it was concluded that users are oriented toward the following types of needs: object perception, mobility, orientation, computing skills, training, and education science. To address these needs, the proposed system aimed to develop a scalable approach to haptic exploration targeted to the following objectives: 1) to form environments that simulate circumstances relating to various levels of training for the blind; 2) to prioritize the needs for haptic conception from very simple to very complex forms; and 3) to set the levels of haptic perception to a corresponding level of usability awareness.

Based on the initial specifications derived by the end user requirements, the goals of the feasibility study are to show that the user can use the proposed system for

1) recognition of the shape of virtual objects;
2) object manipulation in virtual environments;
3) edutainment;
4) knowledge transfer from the virtual world to reality;
5) navigating in complex environments;
6) understanding scale;
7) understanding proportion;
8) cane simulation;
9) interacting with haptic user interface components.

Each of the selected tests contributes to a number of the aforementioned feasibility study goals.

The tests were selected in order to provide strong indications whether the ENORASI system could be used by visually impaired in order to navigate into virtual environments, recognize, and examine shapes and interact with virtual objects. The complexity and statistical significance of each test were selected according to the comments of the users that participated in the pilot tests.

The feasibility study applications selected were: 1) object recognition and manipulation and 2) cane simulation. The most important factor for selecting the aforementioned tests was the demonstration of the system's usefulness when vision is not available. To prove this, tests were chosen to include human actions that support the construction of perception of virtual environments and interaction. More specifically, the object recognition tests can provide information on whether the technology allows the user to understand size and shape of objects and in extent aid him/her in realizing virtual objects in artificial environments (perception of 3-D forms). These tests also introduce the notion of navigation and exploration in virtual environments.

Also, the cane applications are focusing on simulating human navigation in a virtual world, naturally; using the same perceptual cues as they do when in real world situations. By borrowing experiences that users gained from previous tasks, these tests further explore the potential of training visually impaired users in performing every day tasks, in a safe context.

B. Tests Setup

The feasibility study tests conducted were divided in two categories based on the setup used to perform the tests: 1) the desk setup applications and 2) the cane simulation applications.

1) Desk Setup Applications Development: The desk set applications implemented and tested deal with object recognition and manipulation. More specifically, object recognition/manipulation simulation cases provide the user with force feedback when his/her fingertips collide with objects. Force feedback is sent to the user when the distance between his/her fingertip and an object is smaller than a threshold of 0.5 cm. The amplitude of the force is taking a maximum value when the fingertips are in contact with the object and linearly decreases to zero gradually, as the distance reaches the threshold. In some tests, force feedback was accompanied by auditory feedback in order to enhance users' immersion and further assist them in perceiving the virtual environment.

2) Cane Simulation Applications Development: 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 user's 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:

$$F_C = a(1 + \cos(2\pi\omega t)) \tag{2}$$

where a is the amplitude of the force.

The jolt force effect is given by

$$F_J = d\, e^{-\mathrm{kt}^2} \tag{3}$$

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: 1) the cane does not collide with an object and 2) the cane collides with an object in the scene. The corresponding forces applied to the user are: 1) a constant continues force that emulates the force provided by grasping a real cane and 2) a higher-level constant force, applied to the user fingers when the cane collides with an object in the scene.

In the second case, the following three-state force model was examined:

1) cane does not collide with any object;
2) cane hits on an object in the scene;
3) cane is colliding continuously with an object in the scene (e.g., penetrates an object in the scene).

The following are the corresponding forces applied to the users:

1) constant continues force that emulates the force provided by grasping a real cane;
2) jolt effect force;
3) buzzing.

Experimental evaluation has shown that in the first case, the users had difficulties distinguishing 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: 1) 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 and 2) 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:

$$F = a \cdot (b + \cos(2\pi\omega t)) \left(c + d \cdot e^{-\zeta(t-\beta)^2}\right) \quad (4)$$

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

Based on this, 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 users 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).

C. *Test 1: Object Recognition and Manipulation*

The test scenario can be briefly described as follows: the user is navigating in a constrained virtual environment containing geometrical objects. The goal for the user is to recognize objects and reconstruct the virtual environment using real geometrical objects. The feasibility study goals for the specific test include recognition of shape, knowledge transfer from the virtual to the real world, and artifact's proportion understanding.

More specifically, the virtual environment consists of a table with a number of virtual geometrical objects, of different shapes, placed in a pattern on a virtual table. On the adjacent desk, close at hand, a box with a number of physical representations of different geometrical objects, exists. The user's task is to explore and visualize the virtual environment and subsequently try to reconstruct it using the physical models. At completion, the test leader takes a picture of the result, for later analysis and informs the user of the correct placement of the objects.

The specific test was considered 100% succesful if the user could find all the objects in the virtual environment, recognize them and then use the knowledge acquired in the virtual environment to reconstruct it, accurately, using the real, physical models.

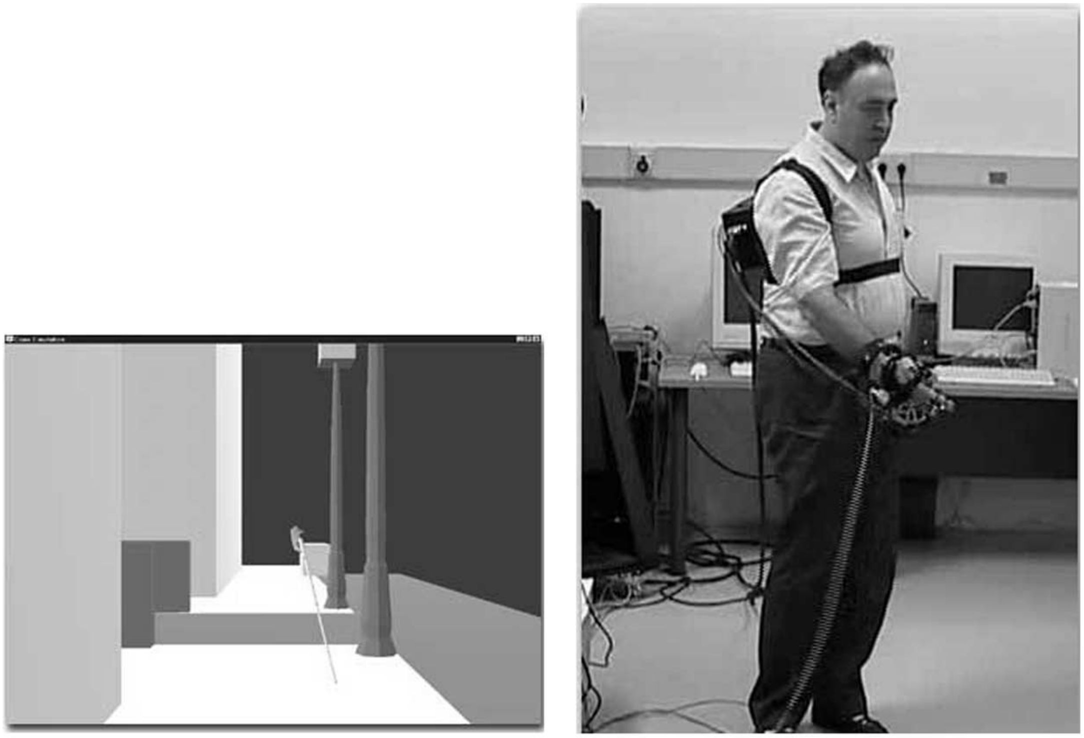
D. *Test 2: Cane Simulation*

The user is asked to cross a traffic light crossing using a virtual cane. Sound and haptic feedback are provided by the system upon collision of the cane with the virtual objects. The feasibility study goals for the specific test include navigating in complex environments, cane simulation, edutainment, knowledge transfer, and interacting with haptic user interface components.

The user is standing at the beginning of the test room wearing the CyberGrasp and a waistcoat for carrying the force control unit (FCU) for the CyberGrasp. When the test starts, the user is asked to grasp the virtual cane. The parameters of the virtual cane (size, grasping forces, 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 1 m on his/her left side. A realistic 3-D 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 2-m-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 specific test was considered 100% succesful if the user could observe all features in the virtual environment (i.e., find the traffic light at the beginning and end of the test, distinguise the difference between the pedestrial street and the road) and react accordingly (wait until the traffic light switches to green, and pass the street following a straight path) within a specific time frame (3 min).



(a) (b)

Fig. 6. Cane simulation—outdoors test. (a) Virtual setup. (b) A user performing the test.

TABLE II
FEASIBILITY STUDY TEST EVALUATION RESULTS

Test	Average Time (min) Blind from Birth	Average Time (min) Non-Blind from birth	Overall Average Time (min)	Success Ratio (%)	Percentage of users needing guidance (%)	Average degree of challenge 1=very easy 5=very difficult
1	12.11	13.23	12.80	92,34	26.90	2.80
2	2.04	2.17	2.12	97,41	3,80	2.65

IV. FEASIBILITY STUDY TESTS EVALUATION

Table II presents the parameters used for the evaluation of the prototype, such as the time of completion/test, success ratio, percentage of users needing guidance and degree of challenge (set by the users). Concerning each test independently, results from Test 1 show that object recognition and manipulation into virtual environments is feasible. The majority of users can understand scale and size of objects. This is an important element for the designers of VR applications for the blind. Results from Test 2 show that blind people can easily navigate in a virtual environment using a cane similarly to what they do in the real world. Cane simulation was considered to be a pioneering application and results have witnessed the acceptance of the users in terms of usability, realism, and extensibility of the specific application.

According to the comments of the users during the tests and the questionnaires filled by the users after the tests, 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. According to the participants, the most important areas which can be addressed very successfully by the system are object recognition and manipulation and mobility and orientation training. It is also important to note that a percentage ranging from 90%–100% of the users have characterized all tests as useful or very useful.

The analysis of variance (ANOVA) [31] method was used to compare the performance of different groups of users. Four different pairs of groups were identified, according to age, gender, blindness from birth or not, and employment status of the users. The time needed to complete each test, was used in order to compare the performance of the different groups. The critical value for the parameter F_{critical} of the ANOVA method was calculated to be equal to 4.25 (assuming probability equal to 0.05 and DOF between groups equal to 1 and within groups equal to 24). Two groups and 26 measurements were assumed in each case and thus parameters DFS and DFG were computed to be $\mathrm{DFS} = 2 - 1 = 1$ and $\mathrm{DFG} = 26 - 2 = 24$.

The age of the users did not seem to affect their performance. Although young users were expected to have a better anticipation on using the haptic devices, older users managed to perform equally or even slightly better than younger ones. The ANOVA results show that there was no significant difference between the two groups in the object recognition case. On the contrary, users over 25 years old performed slightly better in the cane simulation test.

The gender of the users also did not seem to affect the performance results. In the object manipulation and recognition test, male users had slightly better performance. On the other hand, in the cane simulation test, female users performed slightly better. These results should have been expected, because in order for the users to perform the object recognition and manipulation tasks, there is a continuous need to hold their hands wearing the device so that they do not penetrate the virtual objects, which can be considered harder for women. In the cane simulation task, the users were asked to perform more gentle movements. According to the ANOVA method $F_{\mathrm{cane}} = 2.3, F_{\mathrm{object}} = 0.12$ both significantly less than F_{critical}.

In general, results have shown that blind from birth users had similar performance to all other user categories. Blind from birth users had slightly increased difficulty in understanding object shapes and in using the virtual cane. However, this cannot be considered of high importance in order to lead to conclusions relating user performance with blindness from birth. According to ANOVA $F_{\mathrm{cane}} = 0.44$ and $F_{\mathrm{object}} = 0.97$ which are significantly less than F_{critical}.

Finally, the statistical analysis has shown that all employed users had finished the tests successfully. Students and unemployed users failed to successfully complete some of the tests without guidance. This may be a result of the self-confidence that employed users impose. The ANOVA results do not show very significant difference between the means of the groups, but for the cane simulation test $F_{\mathrm{cane}} = 3.29$, which is relatively close to the F_{critical} value compared to other cases, being, however, still less than F_{critical}.

The difficulty level of the tests was reconsidered after completion, according to the percentage of the users that needed guidance and the rank that users gave to each test case. The users were asked to rank the challenge of each test using a scale between 1 (easy) and 5 (very difficult). Both tests were considered by the users to be relatively difficult. The users needed guidance to perform tests 1 and 2 at a percentage of 26.9% and 3.8%, respectively. The average rates of the challenge of the tests, according to the users, were 2.8 for the object recognition test and 2.65 for the cane simulation test.

V. Discussion

This paper presented a very efficient haptic VR tool developed for the training of the visually impaired. The proposed approach focused on the development of a highly interactive and extensible haptic VR training system that allows blind and visually impaired to study and interact with various virtual objects in specially designed virtual environments, while allowing also the designers to produce and customize these configurations.

In terms of usability, we can conclude that the system can be used for educational purposes (e.g., object recognition and manipulation, use of cane), mobility and orientation training and exploration/navigation in 3-D spaces (cane applications).

The main advantages of the system presented in this paper over existing VR systems for the training of the blind and the visually impaired is the capability to: 1) support virtual training environments for the visually impaired with large workspaces (up to 7 m-diameter hemisphere); 2) implement more natural user interaction with the virtual environments (using all fingers of the user's hand); and 3) propose a novel cane simulation system (to our knowledge this paper presents the first system supporting cane simulation in virtual environments for the training of visually impaired). Additionally, the proposed system uses the modified collision detection algorithms that can reduce collision detection time, up to around 50% (for applications utilizing all five fingers—points of contact with the virtual object). Besides the direct benefits of the proposed system, as many of the users mentioned, technology based on virtual environments can eventually provide new training and job opportunities to people with visual disabilities.

Althought the proposed system expands the state of the art, there still exist important technical limitations that 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.

Furthermore, the following conclusions can be drawn from the evaluation of the feasibility study tests in terms of system usability.

1) It was deemed very important to utilize both acoustic and haptic feedbacks, as they are indispensable for the orientation. The majority of the participants preferred to have both feedbacks.
2) Feeling the virtual objects appeared to most of the participants to be very close to real life situations. Balanced proportions in size and complexity enable the user to better feel and understand the objects.
3) Most of the participants were very positive about beginning with simple objects and then proceeding to more and more complex ones. Some of them would have liked to deal with more complex scenarios.
4) All people tested had no problems with the system after an explanation of the technology and some exercises to practice the application.
5) The participants needed little or no guidance at all, i.e., the users had no difficulties to handle the software and the devices. On the contrary, they enjoyed completing their tasks, showed a lot of commitment and were very enthusiastic about being able to have this experience.
6) No connection was found between the age that blindness occurred and the test results.

7) All participants emphasized their demand to use these programs in the future.

VI. CONCLUSION

The result has unanimously been that the prototype introduced was considered very promising and useful, 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 a very large pool of applications. The approach chosen fully describes the belief of blind people to facilitate and improve training practices, and to offer access to new employment opportunities. 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 participant's statements.

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