A Versatile Large-Scale Multimodal VR System for Cultural Heritage Visualization

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ABSTRACT

We describe the development and evaluation of a large-scale multimodal virtual reality simulation suitable for the visualization of cultural heritage sites and architectural planning. The system is demonstrated with a reconstruction of an ancient Greek temple in Messene that was created as part of a EU funded cultural heritage project (CREATE). The system utilizes a CAVE-like theatre consisting of head-tracked user localization, a haptic interface with two arms, and 3D sound. The haptic interface was coupled with a realistic physics engine allowing users to experience and fully appreciate the effort involved in the construction of architectural components and their changes through the ages. Initial user-based studies were carried out, to evaluate the usability and performance of the system. A simple task of stacking blocks was used to compare errors and timing in a haptics-enabled system with a haptics-disabled system. In addition, a qualitative study of the final system took place while it was installed in a museum.

Categories and Subject Descriptors

J.5 [**Art and Humanities**]: Architecture. I.3.4 [**Computer Graphics**]: Three-Dimensional Graphics and Realism – *Virtual Reality* [**Computer Graphics**]: Graphics Utilities – *Virtual Device Interfaces*. I.3.7

General Terms

Experimentation, Human Factors.

Keywords

Multimodal Interfaces, Haptics, Virtual Heritage.

1. INTRODUCTION

Virtual reality (VR) and mixed reality (MR) technologies are now becoming sufficiently developed so that simulations of cultural or architectural sites, or virtual environments (VEs) for design are successful in making users feel truly immersed, especially within CAVE™-like displays utilizing head-tracking. Coupled with interactive technologies that allow visitors of the virtual sites to make their own choices or perform actions that trigger responses from the VE, these virtual experiences become richer and more interesting.

VRST'06, November 1–3, 2006, Limassol, Cyprus.

To date, several successful examples of virtual worlds have been developed for research and design, training, manufacturing, and entertainment. Such environments suffer either from a lack of realism or a low degree of interactivity, due to technological and methodological constraints [29]. On the other hand, haptic interfaces are becoming a common means of interaction with desktop virtual environments. Several experiments during the past 15 years have shown how these interfaces can strongly improve user performance during the interaction with virtual objects [12][15][18]. The ability to reflect digitally programmed forces, representing the contact interaction with the object, increments the user performances and their ability to understand what is happening within the virtual environment [5][6]. Finally, early studies have indicated that the use of a haptic device for virtual reality applications can enhance the sense of presence [23][24]. Presence is commonly expressed to refer to the sense of "being there" in the simulated environment, such that the user loses awareness of the real world props that support the virtual illusion [26].

In this paper we describe the development of a large-scale multimodal simulation as an aid to learning and appreciation of cultural heritage. This application was conceived within the EU funded project, CREATE. The provision of haptic manipulation of objects in the CREATE project was intended to allow a greater degree of realism and enhanced learning in archeological demonstrations and for computer-aided architectural design [30]. One innovative aspect of the CREATE project was the integration of a two contact points haptic interface within a CAVE-like immersive environment in which virtual objects could be projected directly in front of the observer with the ability to grab them and touch them as if they were free standing. This is a significant advancement over desktop simulations in which the user is more aware that they are manipulating a simulated object projected on a screen. One potential problem to consider with the haptic interfaces however is that they could perturb inexperienced users and have the opposite effect than that desired. Therefore, an important requirement for the design of our system was an in-depth study of ease of use.

The particular example described here is that of the Doric temple of Messene, an ancient Greek site that now lies in ruins. The VR simulation allows users to explore and learn about the different architectural members used in ancient Greek temples, specifically their material, positioning and symmetry. This simulation allowed users to engage in a process of reconstructing the temple, thus having a "hands-on" experience of the basic principles involved and architectural components used.

In the rest of this paper, we describe, in section 2, the procedure used for modeling the architectural elements of the Messene site together with the implementation of the VR setup. Section 3 covers the development of the haptic device itself. Results are presented in section 4 with an evaluation of the usability of the haptic interface, which guided its integration with the rest of the VR system together with in situ study of its use by novices and domain experts.

2. IMPLEMENTATION

2.1 Modeling of the Archaeological Site

The first step in creating a realistic environment was to capture the real scene. The chosen approach was to acquire the existing site data that would form the basis for construction and reconstruction of the virtual Messene site. The specific monument chosen for our purposes was the temple of Asclepios in the Hellenistic city of Messene (SW Peloponnese). It is a 4th century BC Doric peripteral temple, relatively large (13m wide x 27m long x 9m high) and simple, built on the remains of an earlier sanctuary of the 8th/7th century BC. The temple is preserved in poor state, but there are a considerable number of architectural members found in the adjacent area, all of them well documented and interpreted by the archaeologists of the Society for Messenian Studies, responsible for the excavation of the site (see Figure 1). Furthermore there is a conventional graphic reconstruction of the temple (several drawings: ground plan, façade, or axonometric drawings), which facilitated its virtual reconstruction. Detailed 3D reconstructions of the existing site as it is today were created by capturing the real scene with modeling-from-images technologies and creating appropriate 3D models. The models were then further modified in a model editor to remove errors and add finishing touches. Capture was conducted in the following phases:

- Data collection for the acquisition of the real scene, with digital photographs of the site. A prototype application was developed with a workflow that allows the user to take advantage of semi-automatic (primitive-based) modeling.
- Post-processing of models to enable interactive display from multiple viewpoints. Multiple textures were captured from several viewpoints. To compensate for camera automatic setups and changes in illumination, the textures were then equalized for color and shadow information.
- Modeling of virtual scene elements, based on additive reconstruction to the scene that would be recreated from the collected material.
- Modeling of dynamic elements, i.e., the building blocks that would be used interactively by users using the haptics interface.

2.2 Display

The VR system ran on a SGI computer, which powered a cubic immersive stereo display, the ReaCTor™ (a CAVE-like environment). Integration of the various (hardware & software) components was a major issue and we used a common platform based on CAVELib™, Performer and the high-level scripting language system XP, which was developed at the EVL in Chicago, and extended by the Foundation of the Hellenic World [14]. XP is a scripting language that provides a high-level interface between the developer and CAVELib™, allowing simple control of all interface aspects. CAVELib™ provides a transparent, platform independent interface to stereo displays, the tracking interfaces and synchronization. Finally, OpenGL Performer™ provided an optimized scene graph and a high-level API built on top of OpenGL.

2.3 Sound

The inclusion of 3D spatialized sound is very important in achieve a truly convincing multimodal experience. In the environment used in the CREATE project a very large number of sound sources were present. The solution was to map a large number of sound sources to a limited number of hardware channels, and is based on perceptual masking, sound source clustering and the use of graphics hardware for audio pre-mixing operations [32].

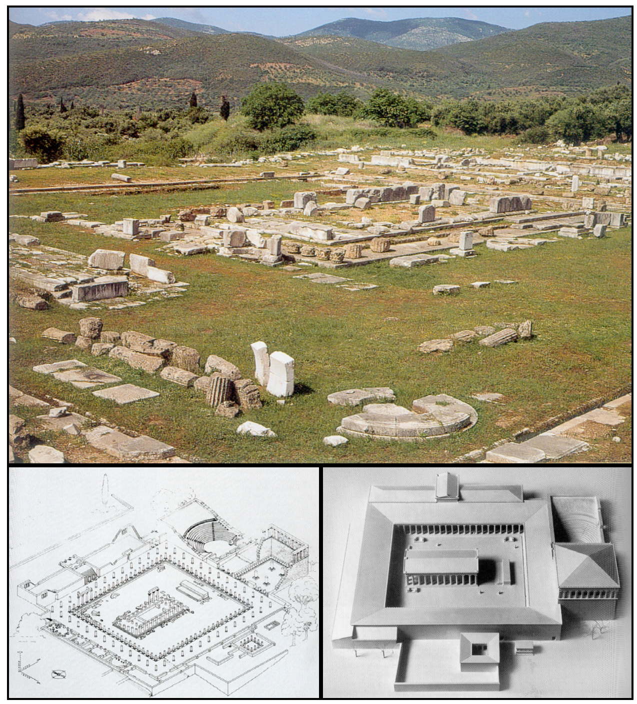


Figure 1. The Messene archaeological site (top) with artist drawing (bottom left) and geometric reconstruction in plaster (bottom right)

2.4 Haptics

Traditional interaction tools for immersive displays such as wands and gloves provide a good starting point for applications targeted by the CREATE project. However, in order to achieve our goal of using seamless interaction methods, we experimented with the development of a haptic interface that was designed specifically for this project to fit the tasks that the user must achieve. The haptic device was installed within the ReaCTor to complement the interaction with force feedback and easier manipulation. The haptic installation together with its evaluation is further described below.

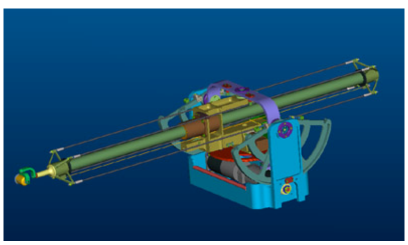
3. THE HAPTIC INTERFACE

The haptic interface was intended for use by a wide range of users, including children. Therefore, the system was designed in accordance with the following requirements:

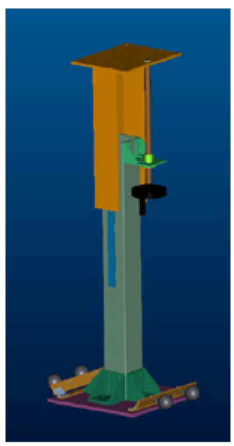
- To be resizable to adapt to the user's height.
- To be robust as it will be used by many different people.

- To have a large workspace to allow large amplitude of movements.
- To have two contact points, so that users could touch, grab and manipulate objects in a more natural way.
- To allow a wide range of exerted forces so as to fit the different tasks, ranging from high frequency texture to large pick forces when grabbing and carrying heavy objects such as columns.
- To adapt to a wide range of display theatres (e.g. cubic, curved-screen displays and single wall displays).

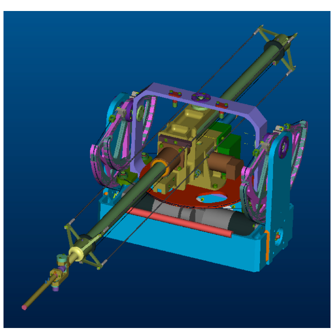
Haptic interaction is accomplished using both hands, allowing more natural interaction. The designed model of the interface as integrated is shown in Figure 3. More details on the mechanical design can be found in [21]. This interface is composed of two equal robotic devices with serial kinematics each having six degrees of freedoms. It is supported by a movable but safe support, which also adapts in height as shown in Figure 2(c). The robot controlling the haptic feedback is shown in Figure 2(a) & 2(b). The haptic interface motors compensate for inertia and the weight of the interface robot itself, making it comfortable and transparent to use. The interface has a maximum pick force of 40 N, an average force of 4N, and a workspace of 60 x 60 x 70 cm.



(a)



(c)



(b)

Figure 2 The haptic interface. (a) and (b) the haptic arm providing the feedback. (c) Support structure that adapts to the user's height.

The capabilities of the haptic interface, which range from surface following, thickness recognition, edge recognition, to grabbing and rotating objects, are increased by the use of two contact points, which were proven better for object recognition through haptic contact [22]. The mechanical sub-system of the haptics interface consists of two identical robotic devices, each having a serial kinematics with a total of 6 Degree of Freedoms (DOFs). For the implementation of the first 3 DOFs, 2 orthogonal rotational pairs followed by a prismatic pair have been selected, while for the last 3 DOFs 3 intersecting rotational pairs have been used to realise a spherical joint. The first 3 DOFs are actuated and sensorised to be able to replicate an independent force vector with an arbitrary orientation on the fingertip and track the position of the fingertip within a large 3D workspace. The remaining 3 DOFs are passive and not sensorised because only the evaluation of the absolute position of the fingertip is required and no moments have to be exerted. This solution allows a very high degree of isotropy of the device with respect to other kinematics solutions. A high degree of isotropy is important in order to achieve a uniform use of the actuators in the workspace of the device and to have a uniform reflected inertia.

Figure 3 Haptic interface placed into the CAVE-like system.

3.1 Control Features

The main control architecture of the haptic interface is represented in the Figure 4. Low level control software has been implemented in order to provide the system with the following main functionalities.

- Manage the communication with Host VE computer;
- Verify, change and store the values for system tunable parameters.
- Provide an elementary safety sound feedback which improves the SW development
- Model dynamics and kinematics of both haptic arms;
- Compensate for non linear effects such as the gravity acceleration on the display and friction.
- Serve the host VE as a position controller (during the wearing phases) and as force display (when used as haptic display).
- Monitor simulation parameters to maintain user safety.
- Generate the correct control motor signals for moving the two arms and for activating the force feedback functionality.

3.2 Control Architecture

All control features had to be synchronised and monitored in order to allow the whole system to correctly execute all tasks requested by the host VE. Moreover, the control system had to present appropriate force-feedback to allow for haptic recognition of small objects, ensure high safety level in all control phases, implement the software interface with host VE computer based on an easy communication protocol, be able to set some system parameters and implement auto calibration features with the arms' relative position and the VE objects.

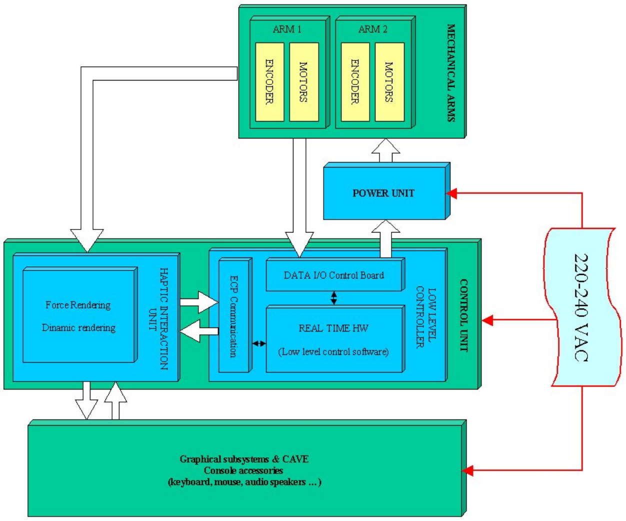


Figure 4 Control architecture of the haptic interface.

3.3 Calibration

Multi contact point virtual environments using haptic feedback share a common problem of coherence. Whenever the interaction between the user and the system makes use of several afferent channels (see [16]), it is required that all the channels have time, force and spatial synchrony. Research experiences in this field demonstrates that the lack of synchronization in one or more of the afferent channels can reduce the sense of presence and result in a sense of unease during the virtual interoperation [6]. The inter-calibration among these components is achieved through a set of semi-automatic procedures described below.

Haptic-graphic calibration procedures: The arm to graphic calibration is achieved by a set of "point and click" procedures. The user is required to place the tip of the haptic device into a set of points which have been graphically produced. Even though the minimum requirement is three points for having realistic match, the procedure is iterated on a larger number of points in order to have a better match that takes into account statistical error reduction and spatial distortion of graphical feedback.

Inter-Haptic calibration procedures: Two arms are yoked together using a simple mechanical device that reduces their relative mobility. This arrangement leaves only 3 translation degrees of freedom to the system and keeps the centre of Cardano's joint in fixed position with respect to the third body of both arms. During the calibration procedure, the right arm is moved under position control while the left one is left free to follow whilst control software computes coordinates of spherical joints expressed in the local reference system of the two arms.

Two local coordinate frames are associated with the right and left arms and an independent frame is set. In order to calibrate the system, a given motion is produced on the master arm. The relative position vectors are calculated for each arm by applying the direct cinematic equations for the mechanical device. A regressive and statistical algorithm described in [19] allows computation of the relative position.

3.4 Integration of the Haptic Interface

The haptic interface was intended to make the placement and positioning of virtual objects more natural as well as provide additional information regarding the character of objects in the simulated environment such as texture, weight, compliance etc. For the haptic interface to function appropriately the following requirements had to be satisfied:

- The provision of visual representation of the contact points.
- Zero or minimal latency between haptic movements and graphical update.
- Transfer of object positions between haptics and graphics systems.
- Communication of user head position within the graphics environment to haptics.
- The ability to indicate to the system which objects are touchable and specify their properties.

Since the haptics interface and the graphics system were controlled by different computer platforms, in order to attain synchronisation between what is felt and what is seen it was necessary that the haptics system had exactly the same geometric environment as the graphics system or at least a subset thereof. Both systems used the same scale virtual workspace. Individual objects specified to the graphics system were made touchable by extending the XP classes. The haptics properties of objects could then also be specified within the XP script files. The geometric objects specified as touchable were loaded onto the haptics PC in advance. At run time the appropriate haptic geometries were loaded by the haptics controller PC and any geometrical transformation specified in the XP script were implemented. Communications between the haptic interface and the host graphics computer were implemented via UDP. The communications network protocol allowed for the transfer of the following parameters:

From Graphics to Haptic Interface

- The position and orientation of the users head as derived by head tracking.
- Specification of objects and their location, mass and orientation to be used in the scene.
- Commands to Enable/Disable haptic force feedback, gravity, and dynamic status of the objects.

From Haptic Interface to Graphics Host

- Object update data.
- User update data.

Object update data included the identity of an object currently being touched and its position and orientation. The user update data included positions of left and right contact points and the control state of 4 physical buttons (2 attached to each stylus). The contact points were represented visually as two spheres. Update rates up to the graphical simulation frame rate were necessary to eliminate visual lag of control points. This was easily achieved as the contact points were updated at 1kHz by the haptic interface and relayed across the UDP network.

One issue was whether the contact points should be proximal or distal; that is, whether co-location between physical end-effectors and graphical representation should exist, since it was shown to be beneficial in other studies [27]. Based on preliminary evaluation in simple stack building tasks it was decided that co-location was neither necessary nor appropriate in this case. Firstly, co-location suffered from occlusion effects whereby the haptic arms prevented the correct rendering of the visual representation of the contact points. Secondly, for the large-scale scene employed in this scenario it was more appropriate that the contact points be location at some distance within the scene. Indeed, for the manipulation of distant objects the position of the contact points could be extended in real-time thus alleviating the need to perform physical user movements within the display.

4. EVALUATION

The evaluation of the haptic interface was carried out in two parts: an initial study of usability and comparison with other interaction devices and an in situ study of the system in a museum.

4.1 Initial Usability Study

We designed a simple test to mimic the process of manipulating weighted virtual objects in order to compare the use of the haptic interface with a standard wand used for pointing, grabbing and manipulating virtual objects in the CAVE-like display. The evaluation we employed required inexperienced users to perform a simple task of stacking objects whilst we measured the time taken as well as other variables.

4.1.1 Procedure

Evaluations were conducted within the cubical display with projections to 3 walls and the floor. The display allows the projection of a scene directly in front of the user, with 3D stereo vision facilitated by the use of CrystalEyes stereo glasses. Head tracking was also used so that when users moved their heads they could observe an appropriate projection of the scene.

The scene consisted of a simulated tabletop, four panels and the three differently coloured blocks that could be manipulated using either the haptic interface or a wand. The wand consists of a small joystick for navigation (not used in the tests) and several buttons that can be used to make choices. The position of the wand within the display is tracked by the graphics computer and may therefore be used to interact with the virtual objects in the scene.

The virtual table top consisted of 3 flat coloured panels lying furthest away from the user and marked the start and end locations of the blocks. Another panel, situated on the table-top directly in front of the user, marked the place where users had to perform the stacking. Users were asked to perform stacking using both the haptic interface and the wand. The haptic interface allowed users to pick up each block and maneuver it into place as if it were a real object, whereas with the wand users pressed a button close to each cube in order to select it, then moved the wand in order to position it at the stacking location. The test involved the following:

1. Users initiated the presentation of the target stack by pressing a button (see Figure 5 below).
2. The target stack was shown to the users at the stacking location for 30 seconds.
3. The stack disappeared and the three blocks were presented at the start panels
4. User initiated the start of their stacking by pressing a button then recreated the stack as previously seen. When stacking was completed users signified this by pressing a button.
5. Users repositioned the blocks to the starting positions as indicated by the color of each panel.

The target stack was created automatically and the coloured order of the blocks constituting the stack was randomized. Users repeated the above procedure 10 times using both the wand and the haptics interface with appropriate randomization to eliminate bias and learning. The stacking time was recorded as the interval between steps 3 and 4 above. The error in the block placement was also recorded at the end of the trial. Both sets of data were written to data files at the end of each trial.

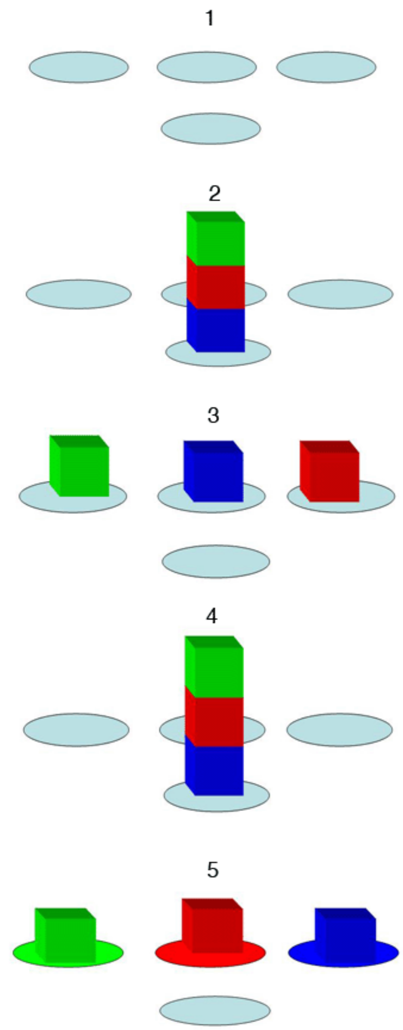


Figure 5. Stages in the evaluation test

4.1.2 Study Participants

We recruited 9 adult participants from within the laboratory and from external sources. All participants received instructions prior to commencement and also had a chance to perform several practice runs before the actual tests.

4.1.3 Results

The time taken to complete each stack as indicated was recorded in fractions of a second and averaged across all blocks and all trials for each condition (HAPTICS or WAND). The averages for each condition and for each block are shown in Figure 6. Results show that the HAPTICS condition required on average around ten seconds more than the WAND condition to perform a complete stack. This may be attributed to greater inertia of weighted objects in the HAPTICS condition. Figure 6 also shows a significant learning effect with stack times reduced by around 5 seconds in the second session for both the HAPTICS and WAND conditions.

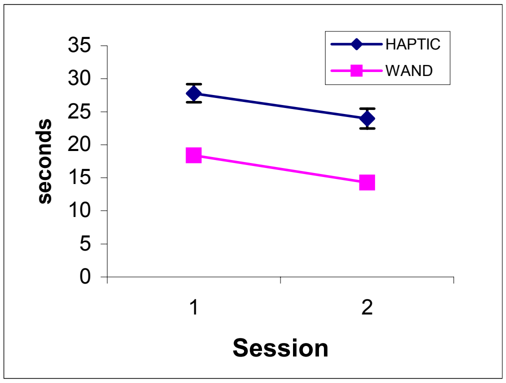


Figure 6. Mean time (seconds) taken to create a stack of 3 cubes for all 9 participants in the study. Error bars show standard error of the mean.

We analysed the Euclidean distance between the stacking positions of the cubes and the XZ position of each cube as positioned by the user. If users positioned the cubes perfectly on top of each other then the error would be zero.

Figure 7 shows the mean percentage error (with respect to the size of the cube) for all users. The results show that the errors for the WAND were the least for both the first and second session. The mean error when using the haptic interface ranged from 15% for the first session to 13% for the second showing a slight learning effect. Once again, the difference could have resulted from the fact that the cubes in the HAPTIC condition had weight and were therefore slightly more difficult to position precisely than in the WAND condition.

The users had to replicate the stack according to its initial presentation with the correct order of red, green and blue blocks. Errors in stacking could result from not paying attention to the original target stack presentation and also from forgetting what order to place the blocks. Forgetting is a function of the amount of time between presentation and replication and also of the amount of mental or cognitive overload.

This in turn could result from having to do a complex task while the user recalls the original stack order. Errors in stack ordering were tabulated for both HAPTIC and WAND conditions. We found that in total 15 ordering errors were made in the HAPTIC condition and 22 in the WAND condition. This total is for all 9 participants. This shows firstly that the task was relatively easy for all participants and that the use of the haptic device did not appear to increase cognitive load.

4.1.4 Discussion

These results show small reduction in stacking time when using the wand compared to the haptics interface. Spatial positioning errors were not significantly different between the wand and haptic interface. However, the differences are slight and may be the result of using a physical model in the case of the haptics interface and no physical model for the wand. More importantly, the results indicate no extensive increase in cognitive workload when using the haptics interface and this showed that it had the potential of becoming a useful component of our VR system.

Overall, the haptic interface is shown to be almost as easy to use as the standard wand with slight increases in stacking time attributed to the greater resistance experienced in manipulating weighted objects with the haptic interface as compared to the weightless objects using the wand.

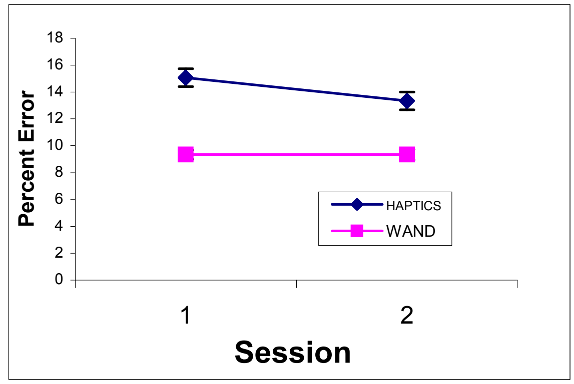


Figure 7. The mean percentage error (with respect to the size of the cubes) for all users. Error bars show standard error of the mean.

4.2 In Situ Evaluation

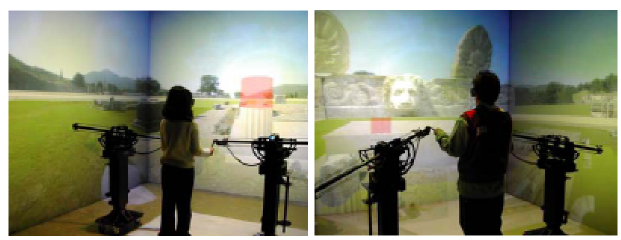


Figure 8. The haptic device inside the CAVE-like display of the Foundation of the Hellenic World, used by young museum visitors to manipulate elements of the Messene temple.

The preliminary usability study described previously was performed in the formative phase of the design and implementation of the haptic interface. Once the interface was completed and integrated with the cultural heritage application, an additional study was performed with the end-users. We tested the archaeological activity environment with expert and novice users in the context of a museum, with three different categories of users: adult novice users (museum visitors), young novice users (museum visitors between 9 and 14 years old), and adult domain experts (archaeologists and educators). All studies took place in the Foundation of the Hellenic World's cubic immersive display, during or after normal museum hours.

Overall, we ran complete sessions and collected opinion questionnaires concerning the haptic interface from a total of 7 domain experts (archaeologists and educators), 32 adult novice users, and 7 children (Figure 8). All novice users (adults and children) were family visitors who spent their day at the museum. The instruments used were questionnaires and informal interviews. A usability questionnaire was used after the experience for all users. Additionally, for the non-expert users, a pre-test questionnaire was used to test prior knowledge and then a similar post-test questionnaire to see if there was a change in their knowledge, as a result of the virtual experience. We also collected general visitor opinions about the haptic interface with visitors of the museum who used it during normal museum hours.

The evaluation of the haptic interface by the content experts involved primarily the usability of the system and its potential as an educational work tool. The archaeologists we worked with and the majority of the archaeologists we evaluated the VE with, were very positive about the overall environment and its potential in educating restoration trainees, mostly because of its ability to present the content in a realistic and accurate manner through sensing the materials and acquiring a sense of weight and natural dimensions. However, most domain experts pointed out that in order for the haptic interface to be used in a real-world workspace (provided that all other practical issues were resolved), the representation of much more detail would be required, as well as the ability to simulate specific restoration techniques, such as filling in missing parts with plaster or treating aging. Nevertheless, most comments emphasized the potential of the haptic interface and provided suggestions for improvement [31].

5. SUMMARY & CONCLUSION

We have presented an immersive multimodal integrated system for evaluation of cultural heritage sites and for architectural design. The system utilises a CAVE-like display and integrated large-scale haptic interface together with 3D sound to make the experience as realistic as possible. Our initial project was the reconstruction and visualization of the ancient site of Messene in Greece. The system was used to create an exhibition for the public whose aim was to teach the process of constructing columns as part of the structure of an ancient Greek temple, but also for archeologists who could use the system as a tool for research. The suitability of the haptic interface in this regard was tested under different experimental conditions in order to determine its effectiveness within the given context and its ability to enhance rather than impede user experience.

6. ACKNOWLEDGMENTS

Our thanks to Dimitris Christopoulos from the Foundation of the Hellenic World, Athens, for help in the development of the system and to the European Union IST program for funding of the CREATE project.

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