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The Museum of Pure Form: touching real statues in an immersive virtual museum

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Abstract

In the Museum of Pure Form, we explore a novel way of presenting art to visitors of a museum, allowing them to virtually touch artefacts in a virtual museum. In order to realise this the statues are first digitised with a scanner so that they can be placed in a virtual museum. The virtual museum is then displayed on a 3D stereo screen. The visitor uses a purpose-built two-contact-point haptic device, mounted on an exoskeleton, to explore the shape of a piece of art which the visitor would otherwise be forbidden to touch in a conventional museum.
We have tested such an installation in a CAVE-like system. The results show that the users are in favour of using a haptic device in this context.

Categories and Subject Descriptors (according to ACM CCS): I.3.8 [Computer Graphics]: Applications, H.5.2 [Information Interfaces and Presentation]: User Interfaces, J.5 [Computer Applications]: Arts and Humanities.

1. Introduction

In the last decade applications in cultural heritage have realised the potential of new technologies of databases for information access and its dissemination to the public. There is now a general consensus that it is essential to create and maintain a repository of museum artefacts and cultural content. While much effort has been put into information database systems, less has been expended on new display technologies for museums. Besides the cost of multimedia installations, one reason for this is the controversy which surrounds the question of whether it is correct to present a representation of an artefact (i.e. not the original artefact) to the public and whether subjective descriptions should be provided or simply omitted to allow the visitors to forge their own opinions.

The Museum of Pure Form [pur] is a 3-year funded project on the IST program of the European Union. The main concept is to allow visitors to touch virtual representations of artefacts presented in a museum. There are four museums which are partners in this project: Centro Gallego de Arte Contemporanea, Santiago de Compostela in Spain [cga], The National Museum, Stockholm in Sweden [nm], The Petrie Museum, London in UK [pet], and the Museum of the Opera del Duomo, Pisa in Italy. All allowed artefacts from their museums to be scanned and presented to the public in the Museum of Pure Form. The Museum of Pure Form is intended to work in conjunction with a variety of display technologies, and its first deployment is within a CAVE-like environment [CNSD93]. Visitors are invited to virtually explore the shape of each sculpture.

As a case study, we tested the Museum of Pure Form in a CAVE-like system, called ReaCToR, into which an exoskeleton-supported haptic interface was integrated. The fully integrated installation is shown in Figure 1. In this paper we explain the entire development from the design and implementation through to the evaluation. In the next section we present an overview of the system. The subsequent sections provide details of the scanning technology and data, design of the virtual museum, system architecture and finally the evaluation.

2. Overview

The Museum of Pure Form is a complete system that includes graphics software, a display system, a haptic device and interface, and a virtual museum that contains representations of pieces of art. Setup of the museum of Pure Form consists of several steps, illustrated in Figure 2. First it is necessary to acquire geometric representations (models) of the artefacts. The models are acquired using a 3D scanner.

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Figure 1: *The Museum of Pure Form tested in the ReaCToR. The user touches the statue via a two-point-contact haptic device mounted on an exoskeleton.*

The raw geometric data from the scan is processed to reduce the number of polygons whilst still maintaining a smooth representation of the artefact. In general the resulting model is used for both graphics rendering and haptics rendering. The Museum of Pure Form is the holistic system which integrates the graphics, haptics and sound modules. Interaction occurs in a CAVE-like environment within which our haptic device is installed. To our knowledge this is the first use of a CAVE-like environment for such an installation.

The following sections detail each necessary component of the Museum of Pure Form.

3. Digitisation

The initial step was consultation with the participating museums to decide which statues to scan. Statues were chosen on multiple criteria: the interest to the museums, the predicted interest to visitors, the availability of the statue, and suitability for scanning. Several factors influence a statue's suitability for scanning. For a statue to be scanned there must either be enough space surrounding the statue (in the physical museum to which it belongs) that it can be scanned 'in place' or it must be transportable so that it can be scanned elsewhere. A statue's suitability for scanning is also influenced by its material. Acquisition of an accurate model requires that the material reflects the beam in the right direction, resulting in reduced geometrical inaccuracies. The shape also needs to be as continuous as possible since holes are more difficult to connect. Despite this, objects such as a cup in copper and a statue in alabaster have been accurately scanned during the project. Scanning was performed by a company called 3D Scanners [3DSa] which also manufactured the scanner. Figure 3 shows a statue and its scanned virtual counterpart.

The scanner used proved particularly suitable for digitising cultural heritage artefacts since it has the following capabilities:

- Scalable - able to scan small items as well as large
- Portable - capable of being taken to the object being scanned and moved around the object
- Able to scan in a variety of ambient lighting conditions
- Capable of scanning a variety of coloured surfaces without spraying the object
- Flexible method of registration avoiding the need for registration stickers
- Self-registering scanning - highly complex 3D objects can be scanned

Other tools and scanners could have been used. Several examples of Digitisation exist in the heritage field. In the Digital Michelangelo Project [Sta, LPCea00] ten statues by Michelangelo, including the well-known figure of David, and two building interiors were digitised. The intention was to produce a set of 3D computer models - one for each statue, architectural setting, and map fragment - and to make these

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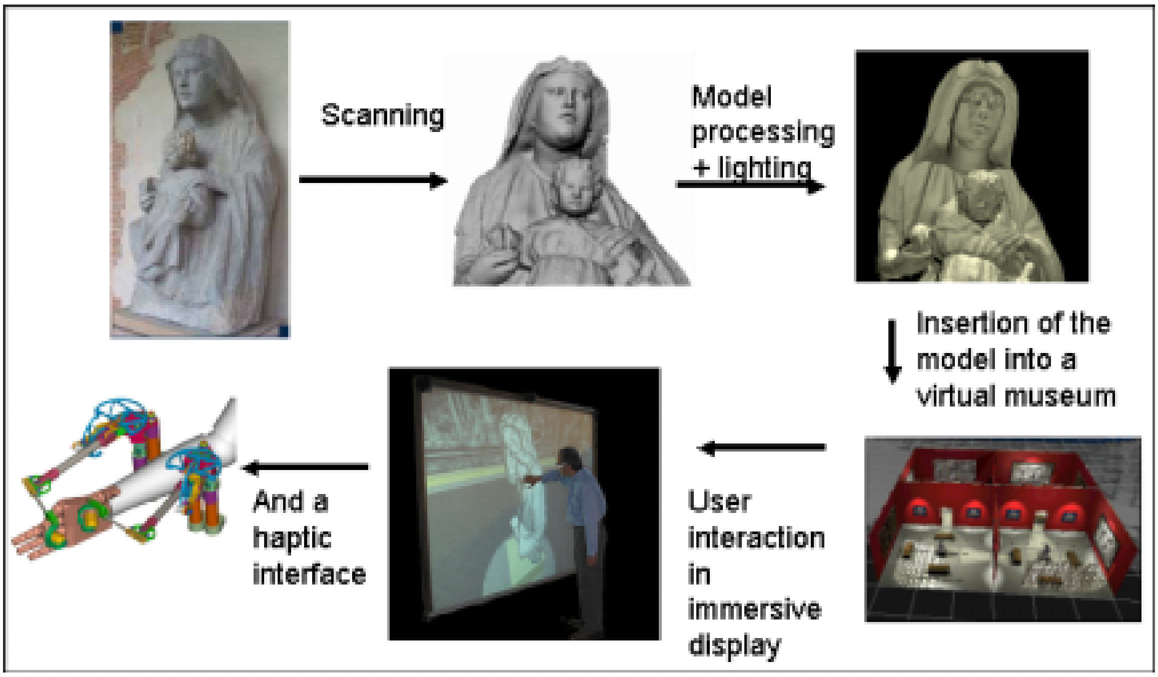

Figure 2: *Overview of the different steps necessary to build the Museum of Pure Form.*

Figure 3: *An example of a statue scanned within the Pure Form project. Left: A picture of the statue. This statue is a shabti presented in the Petrie Museum in London. Right: The scanned model.*

models available worldwide. The aims of the project were to advance 3D scanning technology, to place this technology in the service of citizens, and to create a long-term digital archive of some important cultural artefacts. The project adopted a dual scanning process. For areas of high curvature, areas with chiseling detail and difficult-to-access areas, a 3D Scanners ModelMaker H system in combination with a 12' faro Silver arm was used. On larger areas a 2.5D system specially developed for the project by Cyberware was used. It is not clear from the published results how the data was recombined.

The National Research Council of Canada undertook the Museum and Heritage Demonstration Projects. The aim of these projects is to include, in a virtual museum, collection paintings, sculpture, archaeological objects and sites as well as architectural and historic building elements. The results have shown that information technology can be successfully applied to a variety of traditional applications usually used in a Museum setting as well as to new applications. Such applications include archival documentation, exhibition and display, research, art conservation, archaeology, heritage preservation, replication and, 3D VR theatre and virtual museum activities [BCGR96].

The Visual Computing Group CNR-PISA [Pis] evaluated different commercial technologies for direct acquisition of 3D object shapes (range scanners). The Tabula Cortonensis, a bronze lamina with Etruscan inscriptions on both sides recently discovered in Cortona (Arezzo, Italy), is one of the four main findings with long Etruscan text. A 3D digital model of the "Tabula Cortonensis" has been acquired by using an optical 3D scanning system [BS00]. The Na-

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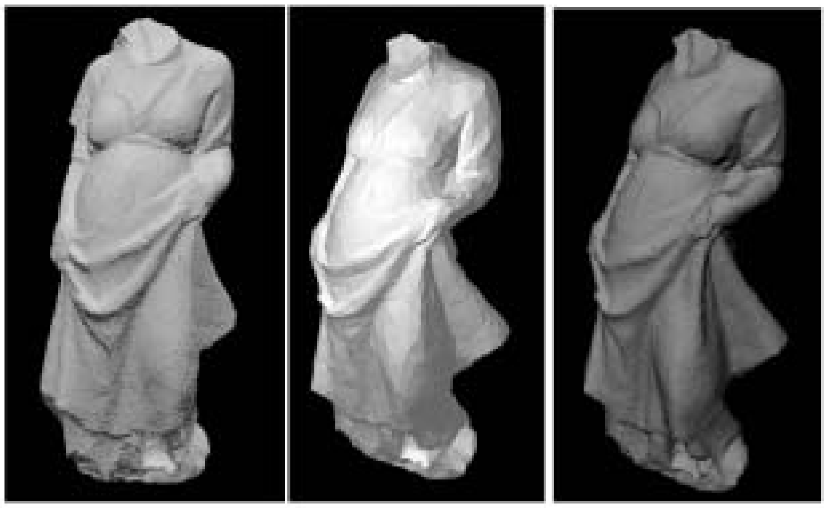

Figure 4: *Left: The mesh as scanned with the 3D scanners technology. Middle: The simplified mesh. Right: The simplified mesh as rendered.*

tional Museums and Galleries on Merseyside [NMG], UK, has been active in the field of laser-based conservation and digitization for many years and have used a variety of scanning systems in their work. Currently they use a 3D Scanners ModelMaker H system and have demonstrated the capability of hand held scanners to scan a variety of objects of differing surface texture and colour in a variety of locations. The Department of Environment (DOE), Northern Ireland have reported on the digitisation and replication of outdoor stone monuments [FM00a, FM00b]. Several monuments in Northern Ireland are suffering from the ravages of the weather. Recognising that severe damage was occuring, the DOE undertook a project to replicate and replace a church lintel depicting the crucifixion at Maghera Old Church with a robust weather resistant copy. The original lintel was still in place at the church but was exposed to the elements. The scanning took place outside in wintry conditions in December 99 in normal lighting conditions.

3.1. Processing of the models

After scanning, each model contains millions of polygons. The mesh is cleaned by removing polygons, reducing the total polygon count to a few thousand. Normals are stored together with the polygons, facilitating smoother rendering and reducing the visual effect of the polygon reduction. This cleaned mesh is used both for the graphics and the haptic renderings. Figure 4 illustrates the raw mesh from a scan and the cleaned mesh used for the graphics rendering and the haptic rendering.

4. Design of the virtual museum

In order to present the scanned models of statues to a visitor, we created a virtual museum. The design of the museum complied with the following design rules:

- The museum shouldn't be a replica of a known museum.
- All statues should be presented inside the Museum of Pure Form, although one in each room.
- The museum should be lit with natural light. Although not photorealistic, the museum should become a pleasant place to visit for the visitors.
- Posters illustrating the historical and cultural context of the statue and its place of origin should be shown in each room. A poster of Pure Form should also be present in each room to keep an identity to the museum.

Additionally we should consider some technical properties:

- The museum should have a geometric complexity such as to ensure real-time navigation.
- The lighting should be computed off line to avoid computation while visiting the museum. Although it prevents modifying the illumination interactively, it allows for higher quality illumination.

A model of the museum was built with 3DsMax [3DSb] that follows each of the set of rules. In this model, a lot of attention was paid to the realism of the rendering, in particular to the lighting. In Figure 5 the model of the museum is presented. At the centre of the room, the user can visualise a scanned artefact. The surroundings of the room reflect both the museum and the geographical origin of the artefact on display. Posters illustrating the physical environment of the sculpture's origins are displayed on the walls. The lighting

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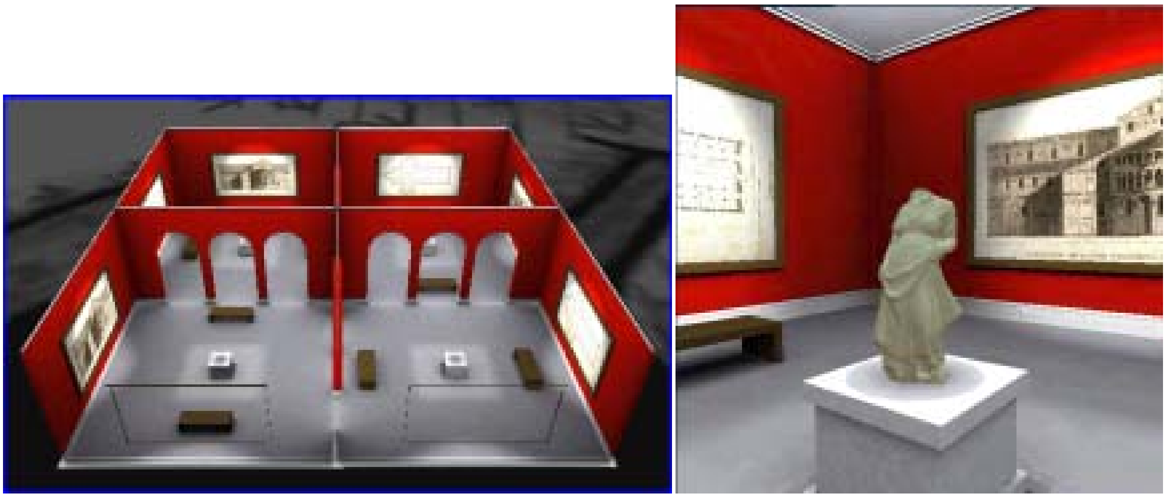

Figure 5: *Left: Model of the Museum of Pure Form. Right: Example of a room of the museum with a statue displayed.*

has been rendered in different levels. There is an illumination provided for the room that was pre-computed with a radiosity solution within 3DSMax. The solution is saved in textures that are mapped on the model. The lighting is therefore fixed but of good quality since it is a global solution. Local lighting is also applied on the statues considering the normals on each polygon. Self-shadows are computed and an environment map is used to compute the diffuse light on the statue. Again, the illumination is saved in textures to avoid computations during the visit.

5. System architecture

The most difficult step of the project is the integration of the graphics with the haptics in an environment such as the ReaCToR. The ReaCToR is driven by a SGI Onyx2 InfiniteReality2 whereas the haptic device and software are controlled from a PC. In this section, we explain how each component of the system fits together.

The integrated system is composed of the following components:

- the haptic interface system
- the database containing the 3D models of sculptures
- the stereoscopic visualization system
- the software API (Application Programming Interface) libraries for the haptic rendering
- the software API libraries for the graphics rendering.

The overall system architecture is schematized in Figure 6. Two computing nodes are in charge of the management of the simulation and control of the Haptic Interface system. The connectivity of node 1 with node 2 is achieved by means of a Fast Ethernet (100 Mbit/s) connection, through a TCP/IP communication protocol. The computing nodes are implemented through ordinary PCs, because a low-cost platform has been targeted as long-term goal. The modules of node 2 run on a Silicon Graphics Onyx2 InfiniteReality2 - this platform allows support of synchronous stereo display to the 4 screens of the ReaCToR. For other types of display they can also run on one PC using Windows2000/XP. Node 2 is responsible for the computation/update of the scene which is simulated in the Virtual Environment (VE). The general VE Scene Manager module, including collision detection, graphics and sound sub-modules, is running on this node. Node 1 is a stand-alone control unit which integrates real-time and interactive computing functionalities through a Real Time Operative System (RTOS). All the modules which control the haptic interface and generate the contact forces on the basis of local interaction are running on node 1 and make use of a real time kernel embedded in the computing unit. Such control device provides adequate computing power in order to execute the required real-time and interactive tasks.

5.1. The haptic interface

Haptic devices are systems devised to exert a controlled force, in response to the surface of a virtual object, on the operator's hand, thus eliciting a sensation of touching the virtual object. The core systems reproducing the feeling of touch within the Museum of Pure Form are two haptic devices. They are capable of exerting forces synthesized in the digital environment on the user's fingers. The choice of two-contact points was justified by a study by Jansson et al. [JM03, JBF03].

The two haptic devices are mounted on an exoskeleton [BFB02, BFB03]. The anthropomorphic exoskeleton HI can be worn on the operator's arm and is particularly suitable for installations in fully immersive Virtual Reality environments, since it avoids optical interferences between the

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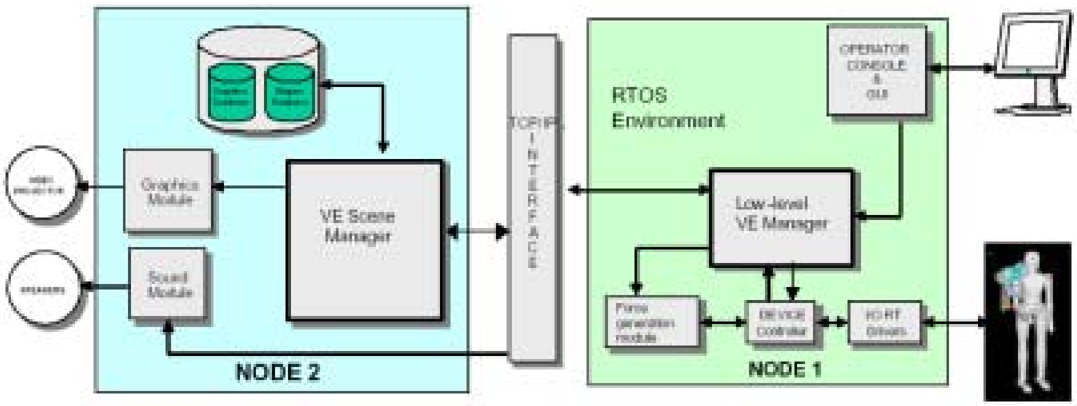

Figure 6: *Architecture of the overall system.*

projection of the image and the robotic parts of the haptic interface. It is composed of two subsystems, the Light-Exos and the Pure-Form Hand-Exoskeleton. The Light-Exos is a wearable afferent-efferent robotic device that allows the user to interact directly with a Virtual Reality System. It is both a sensorized and actuated mechanism, thus allowing the arm position to be tracked and forces to be exerted on it. The Light-Exos can be mounted on a mobile support, which leaves the user free to move around. The Pure-Form-Hand-Exoskeleton (PFHE) is a portable Haptic Interface designed to exert forces of arbitrary direction and amplitude on the index and thumb fingertips, and is coupled with the Light-Exos. The union of these two sub-systems combines the greater workspace of the arm exoskeleton with the higher precision performance of the hand exoskeleton. The calibration of the two-point contact used is described in [AMB04]. The haptic device worn by a user is shown on Figure 1.

A fundamental part of the PURE-FORM system is the subsystem which creates the force-feedback information on the basis of the position data coming from the interfaces and the environment model stored in the system. The generation of the force information is realized by means of a coherence algorithm and is based on the local geometry near the contact point. In the Museum of Pure Form, the forces information considered during an exploration consists of the following:

- contact forces generated during a contour following procedure, i.e. exploration of a shape, or a grasping of a virtual object;
- contact forces generated during a fix contact for evaluating stiffness;
- friction forces generated during a contour following procedure.

It could be argued that the haptic contact should have been located in 3D space exactly at the tip of the haptic device i.e. such that from the user's perspective the haptic and visual senses are co-located. In many ways such colocation is a more naturalistic means of implementing haptics, but other practical and technological issues also come into play. In any VR system displaying 3D imagery there will be an issue with the decoupling of the accommodation (focus) and convergence of our eyes. Convergence can be appropriately elicited by adjusting the disparity of the left and right stereo pair images according to the distance of the object from the eyes. However, accommodation will always be determined by the distance from the eyes to the screen on which the image of the virtual object is projected. This decoupling is not a critical problem in VR systems (at worst it may cause a slight eye strain). However, if we are trying to view a real object (e.g. our finger) that is co-located in space with a virtual object, this gives rise to a perceptual dissonance - we will not be able to simultaneously focus on both the virtual object and the real object. Thus in spite of the fact that we can feel the object at our fingertip via haptic feedback, we will not be able to visually focus on both at the same time. While various means to mitigate this problem were considered, it was also observed that users were comfortable and adept with non-colocated haptic interaction, and it was thus considered non-essential.

5.2. Installation

The Museum of Pure Form was successfully installed in the ReaCToR. The graphics module ran on a 4-pipe SGI Onyx2 InfiniteReality2. The haptic module and the sound module ran on a PC. We observed no user-discernable delay among the communication between the haptic and visual components of the system. The haptic device was placed in the centre of the ReaCToR.

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6. Evaluation

Once the system was installed, we tested how users responded. In particular we were interested in the usability of the system, the quality of the sense of touch, and the overall satisfaction of visiting a museum. We invited a group of computer-literate adults (50% male, 50% female) to take part in the experiment. Some of them had visited a CAVE-like system before, but none of them had previous experience with a haptic device. A simple task was set, the users being asked to explore the shape of two statues under two different sets of conditions.

1. Wearing the exoskeleton and the haptic device but with haptic rendering disabled.
2. Wearing the exoskeleton and the haptic device with haptic rendering software enabled.

Each user performed the tasks in a different order. A period of training was allowed for each user to get used to the device. When the haptic feedback was off, the users had to follow the shape with their hand based on visual cues. Each task lasted 5 minutes. The exploration was accompanied by an audio description corresponding to the statue.

After each condition, the users were asked to complete a questionnaire with 30 questions. The questionnaire was designed to elicit the user's experience in terms of usability, sense of touch and sense of presence. The user could answer each question with a number between 1 and 7 inclusive. Figure 7 shows plots of the data from the questionnaires.

6.1. Usability

The usability of the haptic device was evaluated through a set of questions on how easy it was to learn to use, the ease of recovery from mistakes, and generally on its ease of use, comfort, and overall satisfaction. The mean rating of the usability of the haptic system was 3.2 (Figure 7 (a)), indicating that some aspects could be improved. In particular the exoskeleton was deliberately set too stiff to ensure safety, making the comfort rating quite low.

6.2. Sense of touch

We asked the users how well they could feel and follow the shapes of the statues, and if they found the haptic feedback realistic overall. Results are illustrated in Figure 7 (c) comparing the results for each question with and without haptic feedback. Figure 7 (d) shows the average values for each condition with the standard deviation.

Of course, when the haptic feedback was off, the answers from the users were negative. Conversely, with the haptic feedback on, almost all answers were above the midpoint(4). Users found it interesting to be able to touch, virtually, the statues, and could feel their shapes well. Despite this they didn't find the sense of touch realistic. This could be expected given that the haptic device provides only 2-contact points versus the human hand's natural 5-finger contact capability with multi-sensors. Moreover, the interface between user and haptic device was a thimble at each of the 2 contact-points. The comments of the users reflected a feeling that the contact was first on the thimbles and then on the statue. This reduced their sense of reality when exploring the shape of the statue.

6.3. Sense of presence

Figures 7 (e) and (f) show the results of the questions relating to sense of presence. In particular, we were interested in understanding whether the Museum of Pure Form becomes a reality for users, and whether the use of a haptic device was improving this sense. As can be seen, the results are above average for both sets of conditions, with a better score when the haptic feedback is used. This confirmed that the design of the museum, the presentation of the statues, and the application itself were appropriate. We can conclude that the museum was well designed, and the representation of the statue appropriate in term of modelling and rendering. We also conducted an additional test that confirmed the results. Users were asked 4 questions concerning the room itself (rather than the statue) after the experiment. The results are shown in Figure 7 (b). Users answered with more errors when the haptic feedback had been on, suggesting that they concentrated better on the statue when they could physically touch it.

In general we can conclude that users enjoyed the experiment more when they were able to explore the statue haptically. While haptic interaction demonstrably provides a more interesting experience than when using visualisation only, the difference in response between those users who experienced haptic feedback and those who did not was not as great as we expected. From the user comments, we deduced that they felt intimidated by the exoskeleton. A CAVE-like system is supposed to allow users to feel at ease. Asking them to wear an exoskeleton is contradictory to the idea of free exploration that a CAVE-like system usually provides. In general, devices should be designed to be less invasive when used in CAVE-like systems.

7. Conclusion

In this paper we presented an installation involving a haptic device integrated into a CAVE-like environment in the context of cultural heritage. The Museum of Pure Form contains scanned sculptures that are presented to visitors in a virtual museum. The visitors are allowed to virtually touch the shape of the statues while viewing the artefact in 3D stereo. We have implemented and tested the system through experiments with users. Experimental results show that users prefer the use of a haptic device to explore scanned artefacts. The virtual visit has proven to be a pleasant experience enhanced by the use of the haptic device.

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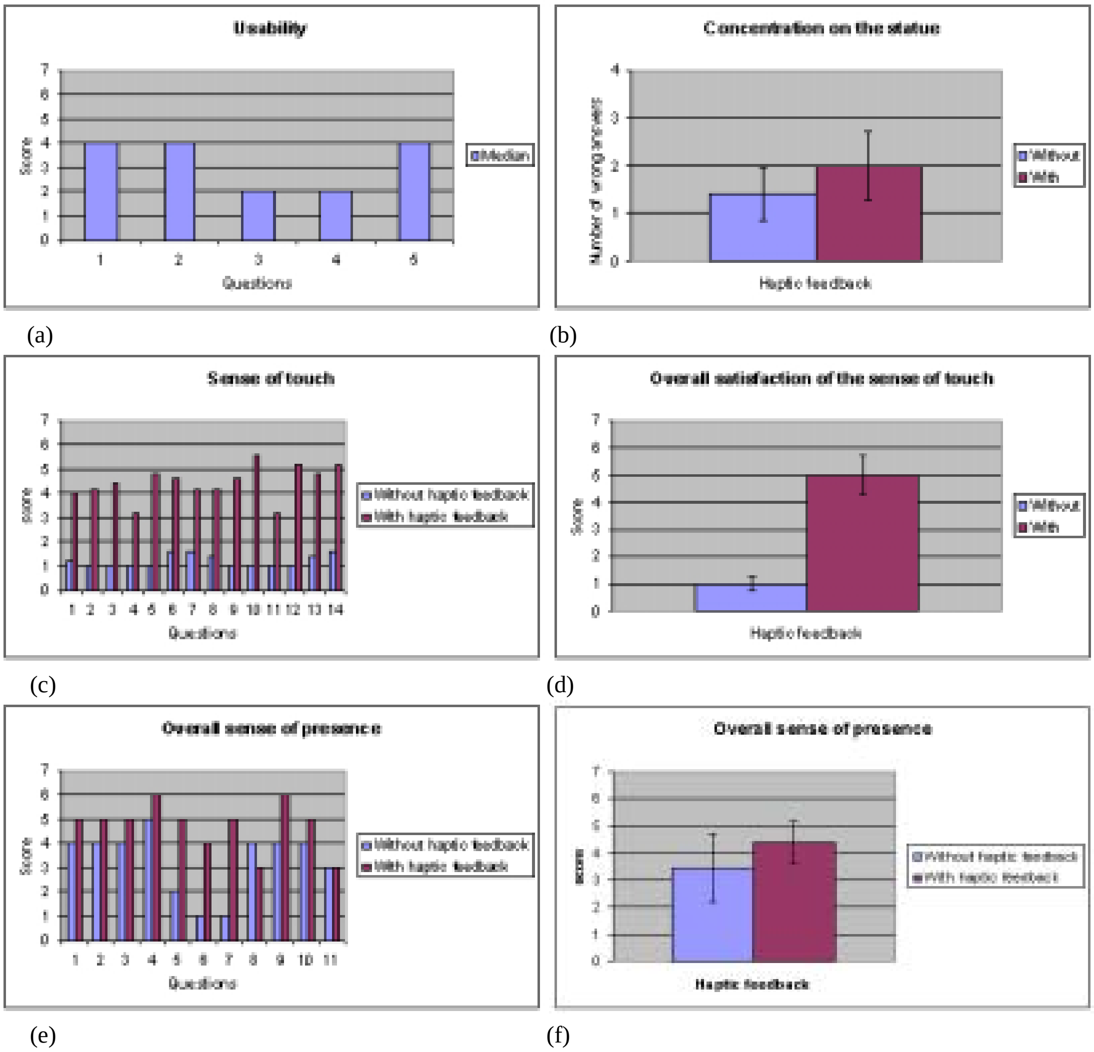

Figure 7: *Results of the evaluation made on the Pure Form system installed in a CAVE-like system.*

We have however identified issues which need to be explored in the future. Firstly, the exoskeleton and its supports prevent the user from feeling at ease in the environment. The users are constantly reminded that they are in a lab (rather than a museum). The design of haptic support structures needs to be investigated in order to produce more user-transparent systems that integrate less obtrusively with CAVE-like systems. Secondly, the development of haptic interfaces is still in its infancy. Using a two-points-of-contact haptic device is a considerable improvement from traditional devices but it still falls far short of the natural haptic sense of a human hand. Combining contact feedback and texture feedback is also an area of research to be investigated. In the Museum of Pure Form only contact feedback was given to the user, whereas the sense of texture would further enhance the experience of users.

Finally the Museum of Pure Form needs to expand to be used in museums and over the web as a digital repository. Displays other than a ReaCToR could be used, and other haptic devices could be built to adapt to each display. It would also be interesting to see other applications exploiting haptic devices to augment the experiences afforded by CAVE-like environnents.

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