Haptics Technologies and Cultural Heritage Applications

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Abstract

This article describes the architecture of the "Museum of Pure Form", a virtual reality system where the user can interact, through the senses of touch and sight, with digital models of 3D art forms and sculptures. Two different realizations of "Museum of Pure Form" systems are currently being developed at PERCRO, Pisa, Italy. In one realization "The Museum of Pure Form" is conceived as a system placed inside several museums and art galleries around Europe and made available to people visiting such institutions. In the second realization the system will be placed and tested inside a CAVE environment.

Considerations on technological aspects concerning the implementation of a virtual environment endowed with haptic feedback for cultural heritage applications are reported throughout the paper.

1. Introduction

The field of Computer Graphic (CG) and Virtual Environment (VE) mediated artistic applications is a novel emerging sector of research. Some museums and universities around the world have started digitalizing their collections in recent times. Digital copies of art collections range from simple pictures to complex 3D images, which can be scalable and can be viewed from different points of view.

Examples of the former are various. C.Vasilakis et al. [1] in 1998 produced a digital three-dimensional reconstruction of the famous Velasquez's painting named Las Meninas; such a work consists of a CAVE [2] like application allowing the users to walk inside the Velasquez's opera.

The Virtual reality is an important concept in the Contemporary Art, because it uses all the chances of Contemporary Society. Nowadays, there are pieces created just for the Net, the Net Art, and many museums have started to collect those virtual pieces. Also, the interaction of the receptor is important. There are some pieces that do not make sense without the public participation. Museums have recently developed a strong interest in technology since they are faced with the challenge of designing appealing exhibitions, handling large volumes of visitors, and conserving precious artwork. They look at technology as a possible partner to help achieve a balance between leisure and learning, as well as to help them be more effective in conveying story and meaning [21].

PERCRO in [4] presented an innovative method for realizing a virtual museum; this application permits a fruition both of paintings and of information related to them. Moreover a rather common example of simple VEs are web sites belonging to all major museums around the world. Users can navigate, using a normal browser, through a digital collection of paintings, sculptures and other art forms commonly referred to with the term of Virtual Tour. Examples of the latter are multiple. The Digital Michelangelo Project [5] developed a 3D model repository; ten statues by Michelangelo, including the well-known figure of David, and two building interiors have been digitalized in order to make these models available worldwide. The Visual Computing Group CNR-PISA evaluated different commercial technologies for the direct acquisition of 3D object shapes. The Tabula Cortonensis is a bronze lamina with Etruscan inscriptions on both sides recently discovered in Cortona (Arezzo, Italy). It 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 [6].

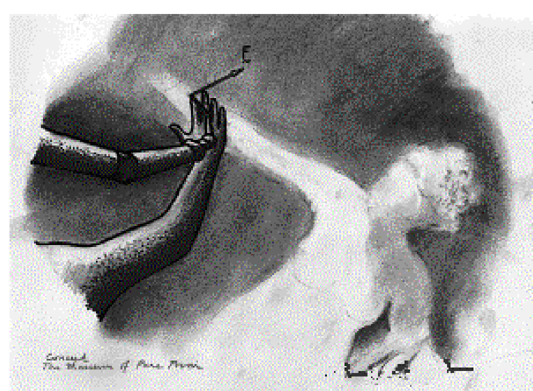

Figure 1. The Museum of Pure Form

Even though these projects have accomplished a great deal of successful results, none of them dealt with haptic perception of art pieces. Every art piece that has been

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digitalized can be viewed with generic instruments, like a browser, or using customized software. However the only sense that is used is that of sight, limiting the user's capabilities, especially in the case of sculptures and art crafts.

The sense of touch is extremely important for anyone who is interested in fully grasping the essence of any 3D form of art. While it wouldn't be reasonable to let anyone touch statues exposed in a gallery, for obvious safety reasons, it can be argued that sight only cannot be enough for someone to fully appreciate every aspect of a 3D art piece that stands in front of them. Surely the perception that an artist shaping an object has of it is very different from the one of a person simply staring at it from a certain distance.

Haptic Interfaces (HI) are robotic systems which allow a user to interact with virtual objects using the sense of touch. This is accomplished exerting a force feedback on the user. HIs have been widely studied in the last decade and have been commercialized by companies as Sensable and Immersion. Examples of HIs developed in an academic setting are numerous. Gregory et al. [7], for instance, have developed a haptic system, called “InTouch", that can be used as a geometric modeler to shape virtual models based on a polygonal mesh representation of objects. Buttolo et al. [8] developed at Ford a system for sculpturing with force-feedback to be used for automotive design.

Many more are the examples of haptic interfaces (HIs) used as synthesis tools in the art field. However, HIs have hardly been used as analysis tools in the same field.

The Interactive Art Museum developed at University of Southern California is the only example found in literature of combining haptic technology with CG techniques, to create a virtual art exhibition where users could interact with 3D objects using both the visual and haptic channel. The system was developed by using the objects of the Fisher Gallery’s collection of teapots, comprised of 150 teapots from all over the world. Two commercial HI, were used to provide to the user a simple single point of contact haptic capability through traditional non-immersive graphical interfaces and commercial haptic devices.

The *Museum of Pure Form* (MPF) (fig.1) was introduced by M.Bergamasco in [10]. Its goal is to radically change the way normal users perceive sculptures, statues or more in general any type of 3D artworks.

The concept of “The Museum of Pure Form” gathers both the interaction procedure and the physical site where the interaction occurs, being these two mediated by the virtual presence of 3D simulated sculptures (or 3D objects). In the Museum of Pure Form it is in fact assumed that sculptures are not physically present as solid 3D entities; on the contrary only synthetic virtual 3D models of the sculpture can be retrieved from a specific data-base (local or shared with other Museum located worldwide). Although the 3D model of the sculpture can be represented and graphically rendered to an external audience on large screen or on HMD (head mounted display), the approach followed in the Museum of Pure Forms refers only to haptic perception, i.e. the capability of perceiving 3D object features (such as shape, hardness, temperature, etc.) by exploiting kinesthetic and cutaneous stimuli. In particular the aim of the visit to the Museum of Pure Forms is that of extracting a direct perception of the sculture’s shape only by haptics. The proposed interaction methodology between the human perceiver (from now on indicated as the “observer”) and the simulated sculpture is based on the development of haptic interfaces exploiting both force and tactile feedback on the hand of the observer. A schematic representation of the operation mode is given in the Figure 2.

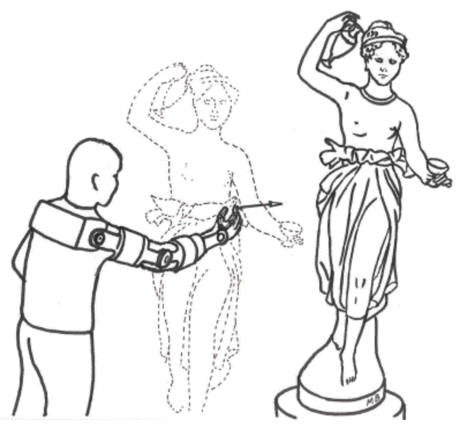

Figure 2. The Concept of the Museum of Pure Form

The differences between the Interactive Art Museum (IAM) and the MPF are multiple. The IAM are generally placed on the Internet or far respect the originals they aim to replicate. Their purpose is to allow visual fruition of works to person, which cannot directly visit the originals. Conversely, MPF systems will be located inside real museums, in close contact with the real art pieces that can be perceived by the users. This will allow anyone visiting the museum to interact with a selected art piece standing in front of them and not with a digital model represented on a computer screen, thus making the overall effect more immersive and, therefore, realistic.

The HI that will be used in the MPF will be specifically designed, controlled and integrated for accomplishing this task, allowing a higher order of haptic realism.

The innovative aspects of the MPF are multiple. First of all, the overall system allows a new and highly innovative form of interaction between visitors and information. Thus, the MPF itself is a novel system that enables a whole new set of services. In addition to this, innovative technical aspects are used in order to make the overall system realistic and user-friendly: the design of force-feedback HIs, the usage in CAVE structure and new haptic rendering techniques applied to sculptures.

Two different realizations of *Museum of Pure Form* systems are currently being developed at PERCRO, Pisa, Italy.

2. The overall architecture

The two different realizations of the MPF (figg.3, 4) will have similar capabilities even though their functionalities, and the context in which they will be used, are slightly different.

In the first realization (Figure 3) the system will be located in a real museum, with real sculptures standing around it. Anyone visiting the museum will be able to normally observe the displayed art collection.

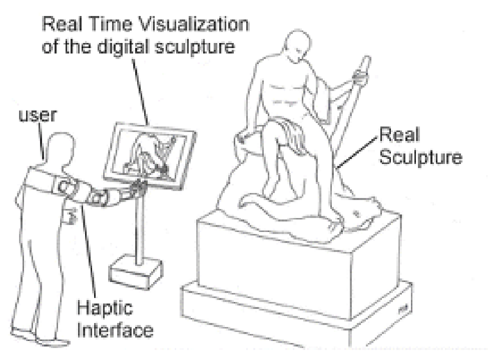

Figure 3. The Museum of Pure Form used inside a real museum

However, the visitor will be allowed to also interact with a digital model of a selected sculpture. Such interaction will be obtained through multiple channels. Force feedback cues will be provided to the user through a HI. As the virtual representation of the user's hand moves along the shape of the digital haptic model of the selected statue, the HI replicates the exact contact forces on the real user. Furthermore, visual cues are provided to the user through a 3D GUI representing the selected sculpture. The purpose of this GUI is multiple. First of all an avatar lets the user know which area of the sculpture is currently being touched. Moreover the GUI allows a more complete visual fruition of the selected sculpture. The overall system will be highly user-friendly and will be located in a normal non-expert environment. Therefore its use will be accessible to any standard visitor of a museum.

In the second realization the system will not be placed inside a real museum. A gallery-like environment, containing a set of digital representations of selected sculptures, will be recreated virtually. Users will be able to navigate through such environment, select a specific sculpture to be examined and interact with it. The overall VE will be visually reproduced inside a CAVE system, which is a multi-person, room-sized, high-resolution, 3D video and audio environment. The interaction with the selected sculpture will be obtained through the visual channel, using the CAVE system, and the haptic channel, using a HI similar to the one proposed for system.

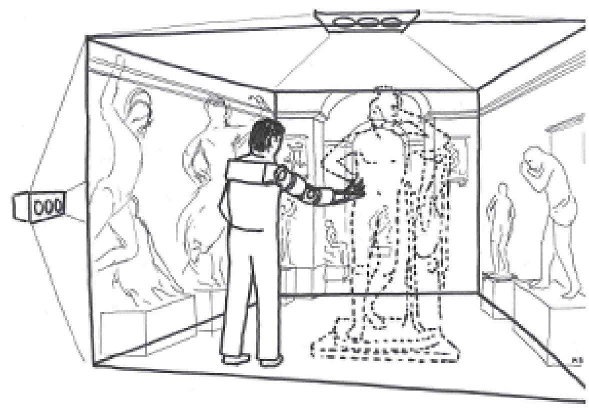

Figure 4. The Museum of Pure Form used inside a CAVE structure

Both realizations will allow a highly innovative and satisfying way to interact with 3D art forms. While both systems allow users to interact with digital haptic models of sculptures through the use of a HI, visual cues are provided to the client in different ways.

In the first realization the MPF system can be seen as a complex analysis tool that can be easily used by people visiting a museum in order to be able to perceive 3D art forms in a more complete way while normally viewing the real art piece. On the other side, in the second realization the MPF system is intended to fully recreate a museum environment and is physically located away from the real art pieces. A key issue that applies to both, however, is that both systems will be used in order to allow users to navigate through the collection of a network of museums, participating to the project. In this case, clearly, the GUI alone accounts for the visual feedback. Such computer network will allow the *tele-perception* of digital copies of sculptures belonging to museums located in geographically different places. Different museums will therefore be allowed to share visual and haptic copies of their art works, thus creating a common European library of sculptures.

The overall structure of the MPF is depicted in fig.5. Digital models of sculptures, located in different museums, can be uploaded by the VR system.

The HI tracks the user's arm and hand positions and sends such information to the VR system. According to the position of the avatar inside the VE and of the position of the art piece, the contacts forces between the two are computed by the collision detection algorithms. These are based on the haptic model of the avatar and of the art piece.

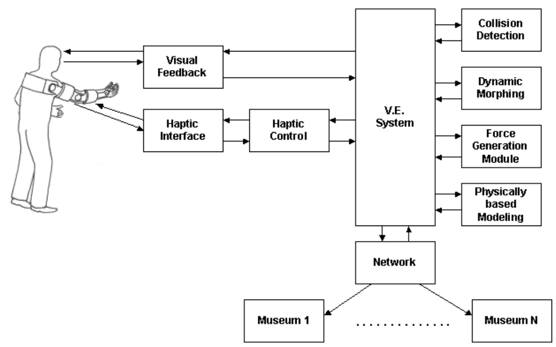

Figure 5. The overall structure

Being the sculpture surface modelled by the computer, scaling factors can be applied to its dimensions in such a way to magnify some particulars of interest of the shape. This is accomplished using the Dynamic Morphing unit. It is important to stress the peculiar characteristic of 3D shape perception obtained only through artificially generated force and/or tactile stimuli. According to the proposed procedure, the observer experiences only the physical presence of the contact point between his/her hand and the virtual surface: the shape reconstruction process is then performed by the observer by dynamic exploration of something (the sculpture) that does not exist in the physical 3D space. This is a new concept of virtual Museum applied to sculptures: it is not a mere digital or graphical 3D representation of the sculpture visually presented to the observer. On the contrary, in the Museum of Pure Forms the observer can directly touch and the physically experience the shape of the digitized sculpture.

The forces computed by the Collision detection unit are fedback to the haptic control unit which exerts them, as closely as possible, on the user through the exoskeleton HI. The avatar's position is also updated graphically.

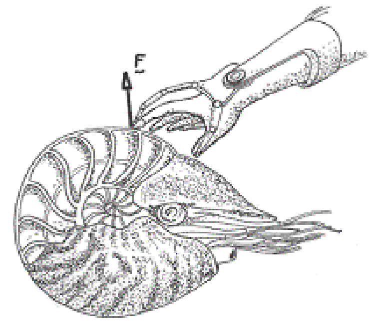

Figure 6. An example of using HIs in the context of natural sciences

The three-dimensional digital acquisition of sculptures will be performed using commercial hardware and software, in different museums, by capturing the geometric features of a selected set of sculptures belonging to their collection and thus constructing a solid model for each statue. At the end of such process, a virtual library of digital models will be created, comprising both ancient and modern pieces of art.

3. The haptic interfaces

The core systems reproducing the feeling of touch within the MPF are two haptic devices. They will be capable of exerting forces synthesized in the digital environment on the user fingers. Two types of HI are under development: an external (desktop like) device and an exoskeleton like device [13]. The presence of an anthropomorphic exoskeleton HI, to be worn on the operator arm (Figure 7), is required in CAVE like full immersive visual system in order to avoid interference problems between the visual rendering component and the links of the HI.

Figure 7. The 5DOF exoskeleton that will be used in the project

A portable HI for the hand with six degrees of freedom is currently being developed at PERCRO (Figure 8). This HI will be mounted on the terminal link of the exoskeleton and desktop like HIs and will provide the operator with the contact point forces on the thumb and index along 3 degrees of freedom. The whole HI system will be capable of tracking the arm movements of the operator and of providing a force feedback on his hand in order to simulate the surface perception.

Both HIs can provide the user with complex force information. This will be accomplished by exerting forces in five degrees of freedom on the operator's arm and forces along three degrees of freedom on his/her index and thumb fingertip. This will allow the replication of more complex force systems on the user while precisely tracking the position of his/her arm/hand without the use of any additional sensor.

The presence of a two fingered interface will allow to simulate contact with rigid surfaces as well as the replication of simple grasp and thickness exploration procedures. Moreover, as shown by Klatzky [16][17], the use of more than one contact point improves the realism degree of the simulation.

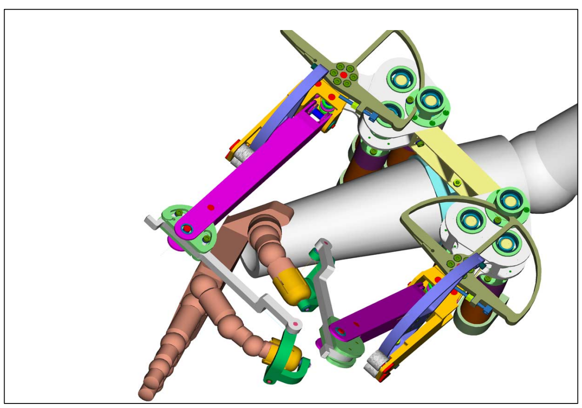

Figure 8. The Haptic Interface for the two fingers

Both haptic devices will be realized in order to show a large workspace compatible with the kinematics of the human arm. The devices will be capable of exerting maximum forces of 10N for each finger all over the workspace.

The interface of the HI towards the VE, which generates the proper force information for both interfaces, is implemented by a common low-level haptic control. Such a type of control receives as input the local geometrical information related to the contact properties and will provide for both interfaces a proper force rendering which ensures the global stability [18][19]. For each finger the force rendering information are generated on the basis of a local geometrical description given as a polyhedral model with n faces:

$$Ax \leq b$$

and the evaluated position of the finger contact point between the HI and the operator.

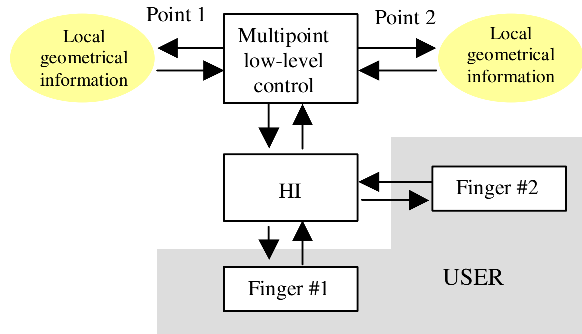

Figure 9. The multipoint low-level control

A parallel (for both fingers) force-shaping algorithm translates polyhedral information into smooth contact forces to be exerted on fingers in such a way that the faces are joined by smooth curves instead of edges [20]. Such a type of force generation allows a two-leveled organization of the collision detection and collision response algorithms and consequently will improve the performances of the whole system.

4. Creating the haptic information

A fundamental part of the MPF 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 into the system.

The generation of the force information is realized by means of a *coherence algorithm*. To each user, which is exploring a piece of art, it is associated a digital subject inside the VE. The association is realized such that the user can really think of being the animated subject created in the virtual space. The digital subject which is moving into the environment is generally known as *avatar*.

The association between the user and his/her avatar greatly simplifies the generation of the feedback forces. In this way, the forces result as they were *naturally* generated into the VE by means of the avatar-environment interactions. The forces felt by the avatar can then be mapped on the user by means of the haptic display. The avatar is modeled to feel a wide set of interaction sensations. Among all haptic information which can be shared during an exploitation session, only data concerned with force information are considered in the following:

- contact forces which appears during a contour following procedure or a grasping of a virtual object;
- contact forces appearing during a fix contact for evaluating stiffness;
- gravity forces related to the weight of the grasped objects;
- friction forces generated during a contour following procedure.

All these kinds of forces are intrinsically related to the contact between the user-avatar and the virtual object. The control of force and graphical feedback is achieved by means of two separate components:

- the determination of the contacts points, the collision detection;
- the generation of the response forces, the collision response.

The collision detection (CD) provides contact information between the avatar's hand and the simulated objects into the Museum. Collision can be checked between the haptic attachment points and the art pieces.

The collision response (CR) component [11][12][20] provides the haptic device control, the information for modeling the contact and replicating into the environment and to the user the effects related to the force exchange.

In fig.10, the role assumed by the different components into the MPF system is shown. Force and graphical loops form different information flows into the system architecture. Such flows are connected each other by means of shared data structures describing the user inputs and the environment data. When realizing this structure on computer architecture, it is necessary to convert an ideal continuous loop into a digitally controlled loop subjected to time and data quantization, computation delays and D/A conversion. Due to hardware limitation these operation will introduce some errors in the controlled loops that influence the exactness of the displayed information (forces and graphics) and the maximum updating frequency.

Referring to fig.10, three different types of loop can be devised in the control scheme. Due to the asymmetrical structure of the human sensory afferent\efferent channels, not all the control loops should be closed at the same frequency. In fact, the *video loop* is strictly related to the capability of graphical resolution of the operator, the *internal loop* is related to the movement capability of the operator, while the *force loop* is in correspondence with the proprioceptive sensors of the operator. The force display requires performances in terms of minimum frequency (and maximum allowable delay) which are more than 10 time (one tenth) those required from the graphical loop.

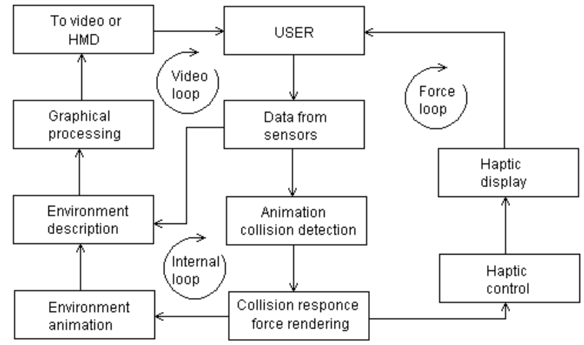

Figure 10. Main loops in a graphical/force VE

This practical constraint justifies the commonly adopted solution of dividing the problem of the force generation in the levels described above. The system performances can be improved since each control loop can be realized at its optimal frequency. Dividing the haptic rendering realization in more simple sub-problems will not only improve the system performances, but also helps the system modularity allowing separate development and testing of the different components.

5. Present developments

With the aim of exploring the basic issues of shape recognition by haptic feedback, an experimental set-up has been realized at PERCRO, based on the force feedback arm exoskeleton (Figure 7).

In the Virtual Environment a full-body avatar of the operator is represented as it is shown in following figures, while the contact forces are displayed as solid arrows. The operator can observe the movements of his arm on a wide screen, on which all the computer generated Virtual Environment is projected. Several objects with different geometrical shapes have been represented, such as a sphere, a wall, a cube and polyhedral objects. The operator can move freely his arm in the space, without feeling the weight of the exoskeleton, since gravity and friction forces are compensated by the action of motors.

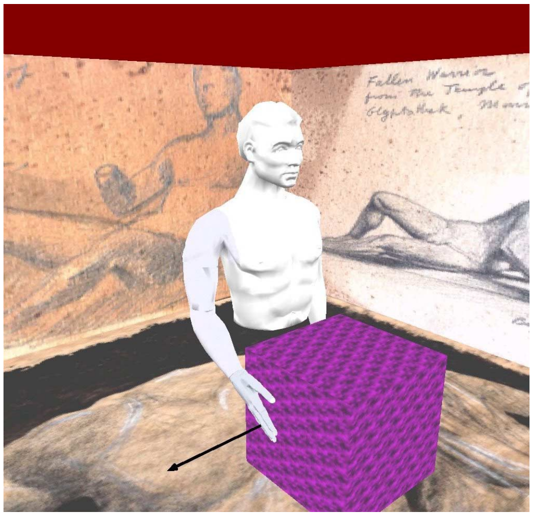

Figure 11. The avatar touching a virtual cube

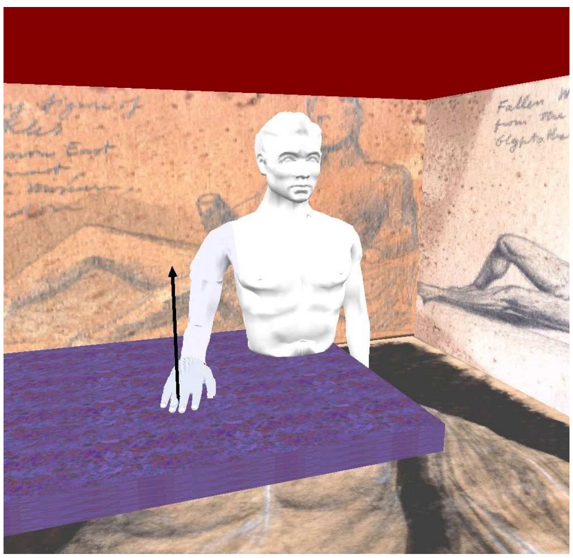

Figure 12. The avatar touching a virtual plane

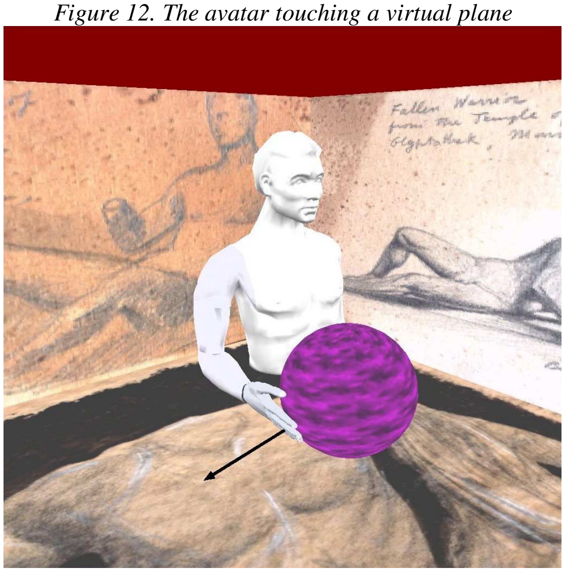

Figure 13. The avatar touching a virtual sphere

The haptic paradigm of interaction will be evaluated from a psycho-cognitive point of view. The most suitable haptic rendering and collision detection algorithms will be selected for the interaction with virtual sculptures. Technical considerations for solid modeling and psycho-perceptive topics will be taken in account and jointly evaluated by technical staff at PERCRO and HCI (Human Computer Interaction) experts. New haptic rendering techniques will be proposed. Some of the problems, still open for a solution, that will be considered, will be the following:

1. What is the optimal cooperation between the senses of sight and touch in order to obtain the most realistic overall perception of an object, and more specifically, of a sculpture?
2. What type of visual cues work better when combined with the use of a HI? Using the combination of the original art piece, which is static, and a simple GUI or reproduce the entire museum setting inside a highly immersive CAVE structure?
3. How should the digital haptic model of a sculpture be designed? Should it be an exact replica of the original art piece? Is it possible to distort some details of the sculpture in order to trick the user providing him/her with a more realistic and informative overall perception?
4. Is it possible to enhance the overall perception of an object, and more specifically of a sculpture, by presenting to the user a haptic model starting from a simplified version and moving on to more complex ones?

Some of these issues have been partially studied in the past in the scientific community [14][15]. However, all of these issues are still completely open. Moreover, past research in the fields of cognitive psychology and human computer interaction, with a focus on haptic and visual perception, have always dealt with simple HIs capable of simulating a single contact point between the operator and a virtual object and with simple GUIs. The highly innovative technology which will be employed in this project, like a highly immersive VE in a CAVE system, a combination of real objects and GUIs representing them, and HIs allowing more than one point of simultaneous contact with the virtual objects, will clearly initiate new research issues in the fields of cognitive psychology and human computer interaction.

6. Conclusions

A highly innovative system allowing users to interact with 3D art pieces through the sense of touch and sight has been presented. These considerations are preliminary. A first version of the system is however in function at PERCRO in Pisa, Italy.

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