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Abstract  Visitors to museums are usually not allowed to touch works of art, which means significant restrictions in the experience of art for visually impaired people. A European research project (PURE-FORM), coordinated by PERCRO in Pisa, Italy, indicates a new option. It aims to make possible manual exploration of virtual 3D copies of works of art via a haptic display developed within the project. A selection of statues has been digitized, and virtual 3D copies of them made available for touching. The final goal is that a virtual library of statues will be created that is accessible at all museums having the necessary equipment.

Key words  Visually impaired; manual exploration; 3D art; haptic display; museum.

Introduction

Objects of art at museums are seldom available for manual manipulation. People with severe visual impairment are currently deprived of direct perception of 3D works of art at museums, as visitors are usually not allowed to touch them. In most cases, they have to rely on verbal descriptions or on 2D tactile depictions of them. The quality of these options is very variable, as is their availability. Further, even with high-quality verbal descriptions and tactile pictures, it is difficult to reach the level of experience obtained by direct contact with the works of art via manual exploration. The understanding of 3D properties is one of the most difficult aspects.

Haptic displays offer a potential solution by presenting a virtual copy. A potential solution to the problem of making 3D works of art available for manual exploration could be haptic dis-
plays (cf. Jansson and McLaughlin et al.). However, such displays developed so far do not offer as rich a haptic information as the information available in natural contexts, where it is possible to pick up information about objects very efficiently by means of manual exploration using up to 10 fingers. Most haptic displays allow only one point of contact between the explorer’s hand and the virtual object, which is a significant restriction. It is similar to try to get information about a visual scene by looking at it through a small hole in a piece of paper moved around in front of it.

**How useful can this restricted information be?** Even if the information is restricted, it may be useful, and it seems meaningful to study the potentials. The situation is more favorable for sighted people than for visually impaired people as vision can compensate for many of the restrictions, for instance, the problems of getting an overview and finding especially interesting parts of the scene. For people with severe visual impairment, the restrictions are more critical.

The potentials of a one-point haptic display as the only source of information have been studied in a number of experiments. For example, it has been demonstrated that virtual textures are perceived as efficiently as real textures, but also that perception of the form of virtual objects is not as good as that of real objects. It is less correct and takes more time, especially when objects are small. Efficiency also decreases with the complexity of the objects.

**What can be done to increase the efficiency?** There are two main methods of improving the efficiency for the user of a haptic display: (1) to train the user in handling the device and (2) to adapt the display to the functioning of haptics.

With regard to training, it has been demonstrated that the efficiency in getting information can be improved considerably by relatively short periods (a few hours) of exercising the special method of exploring with the device. However, there were large individual differences in improvement. A majority of the participants improved their performance, but a minority did not (Fig. 1), probably depending on both capacity and motivation.

Concerning adaptation to the normal functioning of haptics, it can be expected that any change in the design of a haptic display making it possible to present information more similar to the information presented in natural contexts would result in improved performance. Two such possible changes are (1) to increase the number of points of contact between the user and the virtual object and (2) to increase the amount of information at each contact surface. Unfortunately, both developments mean devices that are more technically complicated, as well as more expensive.

An indication of the importance of the first option is an experiment on the identification of real objects with different numbers of fingers. The result demonstrates clearly that an increase in the number of fingers had a very great effect on performance and that the improvement was largest between one finger and two fingers (Fig. 2).
That increasing the amount of information at the skin surface is an important factor was demonstrated for several haptic functions in a study by Lederman and Klatzky. A related experiment on the identification of objects using one and two fingers, respectively, with varying amounts of information available at each surface also demonstrated a significant effect of this parameter on the identification of objects.

The Museum of PURE-FORM The Museum of PURE-FORM is a European Union project aimed at developing a haptic display making virtual copies of objects of art at museums available for manual exploration.

The objective of the Museum of PURE-FORM is to offer museum visitors, students, researchers, blind people, and visually impaired individuals new ways of interacting with 3D works of art through haptic perception (from Greek ‘haptesthai’ meaning ‘to touch’), thus overcoming the traditional limit of art fruition based on mere observation by sight. Although the 3D model of a sculpture can be represented and graphically rendered to an external audience on a large screen or on an HMD (head-mounted display), the approach followed in the Museum of PURE-FORM refers mainly to haptic perception, i.e. the

*PURE-FORM, a European Union project (IST-29580), was initiated and is coordinated by PERCRO, Scuola Superiore S. Anna, Pisa, Italy. The other partners in the project are Pontedera & Tecnologia (Pontedera, Italy), Department of Computer Science, University College London (London, UK), 3D Scanners (UK) Ltd. (Coventry, UK), Department of Psychology, Uppsala University.

Fig. 1. The effects on performance of practice using the special method of exploring with a haptic display. From Jansson & Ivås (printed with permission from Springer).

Fig. 2. The proportion of errors in an experiment on the identification of real objects with varying numbers of fingers used for exploration. From Jansson & Monaci (printed with permission from UNED press).
(Uppsala, Sweden), as well as two museums, Opera della Primatiale Pisana (Pisa, Italy) and Centro Galego de Arte Contemporánea (Santiago de Compostela, Spain). The partners represent different specialties, including technology, computer science, perception, and museum experts. PURE-FORM started in September 2001 and is planned to finish in August 2004.

The capability of perceiving 3D object features (such as shape, hardness, friction, and texture) by exploiting tactual and kinesthetic information. In particular, the aim of a visit to the Museum of PURE-FORM is to make possible direct perception of a sculpture’s properties only by haptics. The proposed interaction between a human perceiver (below named a ‘visitor’) and the simulated sculpture is based on the development of haptic interfaces exploiting force feedback to the hand of the observer. A schematic representation of the operation mode is given in Figure 3.

After entering the Museum, the visitor is provided with an adequate device and is asked to choose a sculpture from the database. Once the 3D model of the sculpture is extracted, the visitor can start the exploration procedure of the virtual sculpture’s surface by performing movements with his/her hand. If no visual information of the virtual sculpture is provided to the observer, the perception of the sculpture’s properties is based solely on haptics.

As the sculpture surface is modeled by the computer, scaling factors can be applied to its dimensions in such a way that some particulars of the shape of special interest are magnified, or a large statue is scaled down. It is important to stress the peculiar characteristic of 3D perception obtained only through artificially generated force and/or tactile information. The experience of the total object is based on the dynamic exploration of something (the sculpture) that does not exist in the physical 3D space. This is a new concept of virtual museums applied to sculptures; it is not a mere digital or graphical 3D representation of the sculpture visually presented to the visitor. On the contrary, in the Museum of PURE-FORM, the visitor can directly touch and experience the properties of the digitized sculpture.

**The Architecture** A prototype of the system is available at the present stage of the project, and it has been assessed to date by a limited number of sighted users only. Its presentation to the general public is planned for September 2003.

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 Program Interface) libraries for the haptics rendering; and
- the software API libraries for the graphics rendering.

The overall system architecture is schematized in Figure 4. Two computing nodes are in charge of the management of the simulation and control of the haptic interface system. The computing nodes are implemented through ordinary PCs, because a low-cost platform has been targeted as a long-term goal. Node 1 is a stand-alone control unit that integrates real-time and interactive computing functionalities. All of the modules, which control the haptic interface and produce the low-level haptic rendering, are run on node 1 and make use of a real-time kernel embedded in the computing unit. Such a control device integrates an adequate computing power in order to execute the required
real-time and interactive tasks. The connectivity of node 1 with node 2 is achieved by means of a Fast Ethernet (100 Mbit/s) connection. The modules of node 2 are run on a PC using Windows 2000/XP OS. Node 2 is responsible for the computation/update of the scene that is simulated in the virtual environment. The general VE (Virtual Environment) Scene Manager module, including high-level haptic rendering, graphics, and sound submodules, is run on this node.

THE DIGITALIZATION OF SCULPTURES The first phase of the project has involved the digital acquisition of sculptures, leading to the

Fig. 3. The concept of PURE-FORM.
Fig. 4. The general architecture of the PURE-FORM overall system. VE, virtual environment; TCP/IP, the standard implemented protocol between computers connected by means of an ethernet; RTOS, real-time operative system.
creation of a virtual repository. Such a repository will be available on the web and at various affiliated museums, and other institutions interested will be able to have access to it. The digitalization process of the sculptures started in May 2002 at the Museo dell’Opera Primaziale Pisana (OPEO, Pisa in Italy), in co-operation with 3D Scanners (UK) Ltd.

Several European museums have contributed to the initiative by supplying digitalization sculptures belonging to their collection. Up to now, a total of 11 sculptures have been digitalized at several museums, including the Centro Gallego de Arte Contemporánea in Santiago de Compostela (Spain), the National Museums in Liverpool (UK), and the National Museum in Stockholm (Sweden). The next scanning session will take place at the Petrie Museum of Egyptian Archaeology in London (UK).

The selection of sculptures belongs to different historical periods. All of the pieces of the OPAE museum belong to the XIII century and represent important pieces of the gothic period of Italian sculpture. Almost all of the selected sculptures are by Nicola Pisano and his son Giovanni, who are among the most outstanding and innovating representatives of Italian sculpture (Fig. 5).

All of the pieces from the National Museums in Liverpool collection (Fig. 6) are part of the Ince-Blundell collection, a large collection of Classical Greek and Roman sculptures collected by Henry Blundell during the late part of the 18th and early part of the 19th centuries. Part of this collection is on display at the National Museums and part at Ince-Blundell Hall.

Pieces from Centro Gallego de Arte Contemporánea (Fig. 7) are all works of contemporary art and exploit the usage of materials other than stone or marble, like wood, fabric, and ceramics. The pieces digitalized at the National Museum in Stockholm also present different
Fig. 7. Digital copy of Augas (1997) by Xavier Toubes from Centro Gallego de Arte Contemporánea, porcelain (97 × 62 × 150/167 × 65 × 56 cm).

Fig. 8. A scheme of the principal phases occurring in the digitalization process.

Fig. 9. One moment during digitalization at the OPAE museum.

Materials; a sculpture in alabaster, for example, has been included in the virtual collection.

The process of digitalization can be mainly divided into three phases: scanning, mesh extraction, and mesh reduction. The connection between the three phases and their relationship with the final products is shown in Figure 8. The mesh reduction phase provides simplified meshes suitable for effective graphical and haptic rendering, since the mesh extraction phase produces models composed of several millions of triangles that are too heavy to be successfully handled.

The digitalization process was carried out by a portable non-contact laser scanner, mounted on an articulated robot arm. The scanning system is based on a digital scanning head that observes the deformation of a laser beam projected on the object. The system is moved around the sculpture to acquire data, without touching it in any way. As shown in Figure 9, the laser-based scanning head is mounted at the end effectors of a robotic faro-arm, which is able to detect its position. By combining the information coming from the scanning system and from the robotic arm, the positions of the object points in space can be reconstructed. The resolution at which the sculpture digitalization was carried out is 0.1 mm.
The acquired point clouds are processed to filter and to reduce data noise and then wrapped in a high-resolution mesh (millions of triangles). Afterwards, the high-resolution mesh is processed in order to fill holes and a low-resolution mesh (a few thousands of triangles) is extracted through a simplification process (Fig. 10).

A bump mapping extraction algorithm has been developed to manage models of millions of triangles in real-time over an ordinary PC and to render the models quickly accessible from the web, too. The bump map extraction software produces a bump mapped low-resolution mesh starting from the high- and low-resolution meshes (see Fig. 11). Basically, the algorithm calculates suitable textures that capture the local geometry of the high-resolution model and afterwards applies them to the polygons of the low-resolution model. Such textures contain information about the geometric roughness of the surface since they encode the local variation of the normals to the surface of the high-resolution model and are used to generate the contact force.

The usage of bump data for rendering detailed properties of materials may be an effective solution for exploiting vibration to enhance...
haptic perception of small details and local properties of surfaces. Vibratory stimulation via a probe has been reported to be useful for roughness perception.\(^{14}\)

**The pure-form haptic interface system** The PURE-FORM haptic system reproduces the contact forces generated by the interaction with the digital model through a haptic interface such that the user may perceive a replica of the forces generated during the contact between his/her hand and the virtual copy, together with the virtual representation of the movements of his/her hand along the surface of the digital model. The display consists of an arm exoskeleton for force feedback on the upper limb (Fig. 12), integrated with a haptic interface for two fingers (Fig. 13). The system has been designed for fixed installations in a given place, so that the supply of electrical power is (supposed to be) available at the installation site.

Arm exoskeleton refers to a robotic structure with an anthropomorphic kinematics that is able to replicate the movements of the human arm faithfully and is built such that it can be worn by the operator on his/her arm.\(^{15}\) Moreover, the arm exoskeleton is able to exert control forces on the contact points with the operator arm according to the state of the simulation, so as to prevent its movements in case it should come into contact with a virtual object. Composite materials, used for its fabrication, combined with a tendon-based actuation permit a light and transparent haptic device. This means that it has a low inertia, allowing the user not to perceive its dynamics when he moves it. It is actuated by four DC brushed torque motors, electrically powered, which can provide forces up to 100 Newton. Its total weight, including both grounded and moving parts, is about 11 kg, distributed such that a ratio payload/weight approximately equal to 1 is achieved. This last figure indicates the maximum load that a robot can sustain under static conditions compared with its total weight; for industrial robots, this load commonly assumes values of 1/20 kg/kg.

The haptic interface for fingers,\(^{16}\) depicted in Figure 13, is intended to be mounted on the end part of the arm exoskeleton. It is able to
exert an arbitrary force of direction and amplitude of less than 15 Newton on the fingers tips. In particular, the forces generated during the contact with sculptures will be transmitted to the operator by means of two thimbles placed on the tips of the forefinger and thumb. The combination of these two haptic interfaces is aimed at providing two contact points for the force feedback on thumb and index fingertips, without imposing limitations to the natural workspace of the human arm during the exploration.

Both haptic interfaces can provide the user with complex force information. This is 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 allows 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.

CREATING THE HAPTIC INFORMATION A fundamental part of the PURE-FORM system is the subsystem that 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. To the user exploring a piece of art, a digital subject inside the VE is associated, commonly known as avatar. The association is realized such that the user can really experience the animated subject created in the virtual space.

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 in 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. Of all the haptic information that can be shared during an exploration session, only data

Fig. 14. An example of haptic interaction with a mesh composed of 20,000 polygons. When the interaction point, representing the position of the user’s fingertip, penetrates into the model surface, a force is generated with a magnitude proportional to the extent of penetration.
concerned with force information are considered in the following list (cf. the categories of exploratory procedures suggested by Lederman & Klatzky):  

- contact forces that appear while following a contour or enclosing a virtual object for perceiving shape;  
- contact forces that appear while pressing a virtual object for perceiving hardness;  
- gravity forces that appear during unsupported holding for perceiving the weight of an object; and  
- friction forces that appear during lateral motion along the surface of the virtual object for perceiving texture.

All of these kinds of forces are intrinsically related to the contact between the user-avatar and the virtual object. The generation of the force is based on the local geometry near the contact point (Figure 14). This geometry is used to rapidly compute the amount of penetration of the contact point within the surface and consequently generate a reaction force to counterbalance the penetration. As a result, a virtual constraint is created to the user’s movements that produces an experience of being in touch with a surface.

The haptic experience realized in this way relies on almost only kinesthetic information, why it cannot reach the same richness as that obtained via the skin of a fingertip exploring a real surface. However, local high frequency oscillations of the applied force may enhance the perception of textures of simulated surfaces (cf. above).

**THE AMBITION TO DEVELOP A USER-FRIENDLY DEVICE** A haptic display such as this one is a technically advanced product that may seem very complicated to a layman. However, PURE-FORM has the ambition that the haptic display should be easy to put on and carry, as well as easy to use, by maximally adapting it to the functioning of human haptic perception. To what extent this ambition is accomplished will be investigated in evaluation studies.

**Conclusions** The development of haptic displays proposes a new promising option for visually impaired people to experience works of art at museums by manual exploration of virtual copies. There are still problems in making the manual interaction with the virtual copies via the displays more similar to the interaction with real objects. Development of the haptic displays to make them more user-friendly is wanted. PURE-FORM is a project aimed in this direction.

References  