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Cultural Heritage

A novel approach to documenting artifacts at the Gold Museum in Bogota

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ABSTRACT

We present our work on novel digitizing techniques to create virtual exhibitions in the context of the Gold Museum in Bogotá, Colombia, a world renown space for precious pre-Colombian gold artifacts. In order to solve issues related to high specular reflection in gold artifacts, we developed a multi-spectral approach that solves some of the shortfalls of many commercial scanners. We also integrated commercial haptic devices into a new virtual installation that allows visitors to touch, hear, and see virtual approximations of the real objects. As an evaluation methodology, we compare the results of a scanner with normal light with our approach, and we also present results from user studies on our virtual installation.

1. Introduction

Pre-hispanic colombian civilizations such as Muisca, Tairona, or Sinu produced beautiful garments, musical instruments, and tools in which they showed their knowledge of goldsmithing and handcrafting of several materials. The Gold Museum in Bogota is the institution responsible for preserving, researching, and exhibiting a very impressive collection of 33,000 artifacts. Most of these artifacts are made of gold, but there are also fine pieces made of clay, bone, or stone. This collection serves as an inspiration for our work on the development of innovative methods for both scanning gold objects and creating virtual multi-modal[1] installations.

Most commercial 3D scanners use optical triangulation of a laser, a process that fails in the presence of high reflectivity and shininess, as in gold artifacts. The usual way to handle this problem is to cover an artifact's surface with a chemically inactive, reflective coating such as special talcum powder, that will diffuse the incoming light. However, talcum's adherence to a surface may vary, so the scanning of gold artifacts can still fail. In this paper, we use a long-wavelength ultraviolet (UV) light source for optical triangulation, which allows us to reduce the specular properties of a material during 3D data acquisition. Our implementation is very practical and only requires to modify the light source of the Minolta Vivid i9 3D scanning system.

A great part of the Gold Museum's collection is composed of small pieces that should be both admired by visitors and preserved for future generations. These competing goals force museums to enclose small artifacts behind glass displays with careful lighting, which fulfill the preservation requirements but also limit the ability of visitors to observe those objects in detail. Moreover, some artifacts may have specific weight and sound, but those features are usually hidden in traditional displays. In this paper, we show a novel multi-modal setup that allows visitors to touch, hear, and see 3D virtual approximations of small artifacts. Such multi-modal interface allows Museum visitors to complement their traditional experience with the real objects behind a glass with an interactive experience with virtual approximations. 3D models produced by a 3D scanner can be integrated using extra information from high-resolution cameras, video cameras, weigh-scales, and sound from high-quality microphones, in order to create a full multi-modal database that can then be displayed to visitors by means of virtual reality technology. Moreover, the same content can be used in the creation of standard web and multimedia contents, so visitors can enjoy the material using different interfaces.

This paper is organized as follows. Section 2 presents an overview of related work concerning data acquisition and multi-modal installations in a virtual heritage context. Section 3 presents the system for data acquisition focusing in the digitalization

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[1] A multi-modal presentation is defined as a system that gives information to a user through more than one sense; in this paper through sight, hearing, and touch.

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of shiny gold artifacts. A description of the proposed multi-modal system and a user evaluation is presented in Section 4. We end with conclusions in Section 5.

2. Related work

We are specifically interested in data acquisition and multi-modal installations. The field of virtual heritage is very wide nowadays, with several initiatives with similar foci that should also be mentioned, from early collections of results [1] to large international projects [2].

Related to 3D data acquisition, most previous work has been oriented to the digitalization of artifacts or outdoor scenes that do not have the reflective issues of gold. Guidi et al. [3] present a system to obtain 3D models of imperial Rome, using a long-range 3D scanning with enough resolution to be able to show small details. Brusco et al. [4] propose a system for the automatic construction of multi-spectral 3D models of historical buildings using a custom multi-spectral camera. Landon and Seales [5] introduce a system for the digitization of petroglyphs and iconography. Pollefeys et al. [6] present an approach that can capture the 3D shape and appearance of archeological artifacts, monuments, or sites from photographs or video, mostly targeting large sites. Blais and Beraldin [7] combine 3D laser imaging with geometric calibration and texture mapping with perspective correction in order to have a perfectly synchronized 3D model with its texture. Using on-site geometric calibration of the intrinsic and extrinsic parameters of the laser scanning process they were able to digitize cultural icons like the Mona Lisa at The Louvre. Finally, there have been systems capable of capturing physical characteristics other than shape, such as the work by Pai et al. [8] who measure mechanical properties at different positions, or Corbett et al. [9] who measure the sound that artifacts emit when struck. Although we are not using all the same complex apparatus, our work was inspired by Pai and Corbett as we try to measure more than just one modality per artifact.

In terms of multi-modal installations, it is of interest to incorporate haptics[2] and stereo display capabilities to exhibitions to allow visitors to explore, touch, and see the artifacts more closely. There have been several virtual heritage applications that have incorporated haptics in their interface development. In the CREATE project, Christou et al. [10] show an installation that uses a CAVE environment, a tracker, and two large haptic devices to create a realistic experience of manipulating artifacts from ancient Greece. Tecchia et al. [11] present a multi-modal exhibition with high-end haptics and stereo display, as well as a virtual gallery on the Internet with a selection of sculptures from several Museums involved in the project. A sophisticated haptic device is used in Bergamasco et al. [12] in order to explore the shape of Museum artifacts, specially sculptures. Although these setups promise to create a very real haptic experience, they are probably too costly and fragile for most museums. Laycock et al. [13] present a system in which a simple haptic device (Phantom Omni) has been integrated into a high-quality pre-rendered environment, mostly for navigation.

In terms of usage, Bergamasco et al. [12] describe two systems, one where users are in front of a physical artifact and one in a virtual setup. In the first one, visitors are positioned in front of a sculpture where a haptic device allows them to explore its shape. An extra display gives more information, such as the current point of contact. In the second system, visitors are in a CAVE-like environment in which they can see a virtual replica of an artifact in stereo and interact with it. Christou et al. [10] present also a CAVE-like scenario for the exploration of large scale archeological sites. Tecchia et al. [11] use a virtual setup similar to one presented in Bergamasco et al. [12]. Brewster [14] describes an exhibition in the Hunterian Museum at Glasgow University targeted to blind visitors. This system allows visitors to feel the edges and differences in height in some carefully selected artifacts by using a haptic mouse. Mclaughlin et al. [15] developed a system for collaborative, remote haptic exploration of artifacts, based on heterogeneous setups composed of Phantom and cybergrasp devices. Petridis et al. [16] present a multi-modal system that uses some new devices, such as a space-mouse and artifact replicas manufactured by a 3D printer.

In terms of usability studies, Burke et al. [17] have shown that additional modalities to visual feedback such as touch and sound improve performance. Butler et al. [18] suggest that visitors might take more time looking at an exhibition when their interface involves haptic devices. Asano et al. [19] suggest high expectations on exhibition planners and visitors about haptic enabled displays of artifacts in remote museum applications.

3. Data acquisition

We begin by describing our scanning process; from our first experience at the Museum to our contribution to scanning of 3D gold objects. In order to offer Gold Museum visitors a multi-modal system in which they can see in stereo, touch, hear and weigh each artifact, we used different digitizing technologies to assure we had enough data for the interactive experiences. In the following list, we characterize each technology by name, by types of attributes we were able to collect, and how these attributes can be displayed to the visitor.

- A Faro/Kréon digitizing arm was used to capture data at high resolution (50 μm) with no texture. This scanner allowed us to eliminate digitizing errors created by the reflectance of gold. It was easy to control integration time vs laser power and to take views away from specular reflections. Most of our models were produced with this scanning technology. Because its sensor did not provide us with registered texture, post-processing was necessary in order to add high-resolution textures to the model using a photogrammetric technique.
- We also experimented with a Minolta 3D laser scanner, which captures data at medium resolution (0.1 mm) with real textures. The data cleaning time was much longer than with the Faro system because it is not possible to control both lighting and sensor orientations. Also, many of the artifacts were at the limit of the sensor resolution and field-of-view, and therefore modeling and view integration were more difficult to achieve.
- NextEngine, a low-cost 3D laser scanner which captures models at low resolution (1 mm) with real textures was tried. Although cleaning time was longer compared to the two previous systems there was no real control of the views or laser power.
- We made two sets of high-resolution pictures, one with markers in order to facilitate texture registration and one with a black background for texture mapping and web-based display. A turntable for rotating objects and fixed light positions was used to obtain all perspectives. Each picture was taken at the highest resolution of our camera (13 M), and camera parameters (focal length, aperture, etc.) were manually fixed.
- Capturing high-quality sound from selected pieces: our purpose was to capture high-quality sound from selected pieces and get an idea as to how an artifact may sound when struck

[2] Haptics in this context relates to devices that simulate the sense of touch.

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with a stylus. This information was captured from a directional microphone ready to be used without modification.

- Information such as complementary text and images related to each artifact's origin, location in the Museum, and description was provided by curators at the Museum.

All 3D scanning devices used throughout the project had problems with the shiny surface of gold artifacts. We were forced to use a chemically inert talcum powder in order to reduce reflectivity and in many cases we had to integrate numerous views to stay away from specular conditions. From this experience, it was concluded that we had to find a better solution to this problem if we wanted to scan full collections at a reasonable speed. For this reason, we developed a non-invasive 3D data acquisition technique for digitalization of highly reflective artifacts. The technique uses an ultraviolet (UV) light source that has been shown to significantly reduce the reflectivity of gold and in other metallic materials. The wavelength range of UV light used is from 315 to 380 nm which corresponds to UV type A (UV-A). UV radiation is detrimental for the health, especially for the eyes (250–300 nm) and for the skin (280–315 nm). Although the UV-A radiation has less effects in humans health, looking for the minimum health risk, it was defined an acquisition protocol in such a way that during the acquisition the worker was not exposed directly to this radiation. The acquisition system uses a dark room with a turntable and the light source is located on the top. The acquisition protocol consists of: (i) to place the object on the turntable before turning on the light source; (ii) to activate the digitalization of the object; and (iii) to remove the object after the UV light has been turned off. The following is the description of our device and procedure.

3.1. 3D data acquisition using a Minolta Vivid i9 System

There are several commercial 3D scanning devices based on active triangulations [20,21], which tend to be very sensitive to the optical properties of an object's surface. One can classify the optical properties of many objects as homogeneous and inhomogeneous [22,23]. In optically homogeneous materials the light reflected is directed to a narrow range of viewing angles. Metals, glass, and crystals are the most common examples of homogeneous materials. For smooth surfaces such as metals this type of reflection is called specular. On the other hand, optically inhomogeneous materials diffuse the reflect light in all directions due to the randomness of their surface micro-structure. This type of reflection is present in materials such as paper and fabric, and it is called Lambertian.

Commercial 3D digitizing systems assume that the object's surface is opaque and Lambertian. Geometrical digitization of highly reflective surfaces require complex optical setups. One of the most common methods is to project a known pattern of light on the object's surface [24–27]. A 3D shape estimate is performed using a phase-shift algorithm based on a single camera observation. Kutulakos et al. [26,28] developed an algorithm in which they assume that only one reflection occurs along a ray. The 3D shape of specular objects could be recovered by three viewpoints if incoming light undergoes two reflections or refractions. Park and Kak [29] introduce the concept of multi-peak range imaging by considering the effects of inter-reflections, which creates multiple peaks in the range sensor. An excellent review of the relevant literature can be found in [30].

Previous techniques for the 3D acquisition of specular objects require specialized and expensive hardware (or major changes to standard 3D digitizing software). We developed a non-invasive technique for the acquisition of specular objects such as gold, steel, silver or copper objects. The technique is based on optical triangulation using a long-wavelength ultraviolet light source. Since optical properties of object surfaces vary with wavelength, one can use multi-spectral 3D acquisition to counteract the adverse effects produced by the high reflectivity. In comparing the reviewed techniques, our proposed solution only requires the modification of the illumination source of the system. Our main idea is that optical properties of objects are very different under different wavelengths. For instance, for digitalization of gold parts it is possible to use illumination with wavelength in the range from 200 to 500 nm, which reduce the reflectance level of gold. Particularly, a wavelength around 470 nm which corresponds to blue illumination could be a good election, not only due to the effect in reflectance but also because it is not dangerous to health. However, besides the low cost, we decided to use, a UV-A illumination lamp of 20 W, with wavelength around 350 nm, because we wanted an illumination system that allows to reduce the level of reflectance of multiple metallic objects like gold, silver or steel. These materials are quite common in artifacts displayed in Museums, such as the Gold Museum in Bogotá. For instance, the percentage of reflectance of these metals to a wavelength of 350 nm is approximately of 34%, 50% and 67% for gold, steel and silver, respectively; whereas at a wavelength near to 450 nm it is approximately of 34%, 55% and 92%, respectively (see [31,32]).

3.1.1. Multi-wavelength optical properties

For our implementation we used a commercial active triangulation system based on structured light by Minolta (Vivid i9 System). In order to understand the relevance of using multi-wavelength lighting in the acquisition process, we present an analysis from the physical viewpoint of the optical characteristics of the object's surface to be digitized.

The reflected light from a surface depends on the type of surface (specular or diffuse), its orientation, the position of light sources, and the position of the CCD that will capture the image. Let θ_i, θ_r and θ_t be the angles that the incident, reflected and refracted light rays make to the normal of the surface, respectively. So, according to the law of reflection for specular surfaces (as those of gold) $\theta_i = \theta_r$, and according to Snell's law $\sin(\theta_i)/\sin(\theta_t) = n_t/n_i$, where n_t and n_i are the refractive indices of the two media [31]. Given a light source, a surface, and an observer, the reflectance model describes the intensity and spectral composition of the reflected light that will reach a sensor. The intensity of the reflected light is determined by the intensity and size of the light source, and the surface optical properties of a material [33]. The percentage of reflected light (R) (Eq. (1)) is determined by the wavelength of the light source and the behavior of the surface at such wavelengths:

$$R = \left(\frac{n_r \cos\theta_i - n_t \cos\theta_t}{n_r \cos\theta_i + n_t \cos\theta_t}\right)^2. \tag{1}$$

Eq. (1) is known as the Fresnel equation. When the light is at near-normal incidence to the surface ($\theta_i \approx \theta_t \approx 0$), as is usually the case for 3D digitizing systems, the reflection coefficient can be approximated by

$$R = \frac{I_r}{I_i} = \left(\frac{n_r - n_t}{n_r + n_t}\right)^2 = \left(\frac{n'-1}{n'+1}\right)^2, \tag{2}$$

where I_r is the reflected intensity and I_i is the incident intensity, and $n' = n_r/n_t$ is the relative refraction index. For metals, a complex index of refraction is used, so $n' = n + ik$, where k is known as the absorption index, and both n and k are functions of the wavelength (λ) of the incident light [31]. Then, the reflected

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intensity as a function of the wavelength, becomes as shown in the following equation:

$$R(\lambda)=\frac{(n(\lambda)-1)^2+k(\lambda)^2}{(n(\lambda)+1)^2+k(\lambda)^2}. \quad (3)$$

Optical properties vs wavelength: Optical properties of metals are related to the interrelation between materials and light properties such as wavelength and intensity. The interaction between light, from an external source, and the electronic structure of a material, creates multiple optical phenomena such as: (i) energy transfer from the light to the material, in which case there is absorption; (ii) energy from light excites material electrons, which emits photons of identical energy once they return to their initial state, so reflection occurs; and (iii) light does not interact with the electronic structure of the material, so there is transmission. In any of these three cases, there is refraction due to changes in the light's energy.

The particularities of light reflection from gold surfaces are due to the presence of a large number of electrons that are weakly connected with their own atoms and therefore can be considered almost free. Since the density of free electrons is high, even very thin layers of metal reflect most of the incident light and in general, are practically opaque. With UV light, optical properties of metal depend mainly on the behavior of the lower bound electron levels (like K and L), that are characterized by their own frequency located in the zone of shorter wavelengths. The participation of these electrons determines the so-called non-metallic optical properties of gold.

Fig. 1 shows the reflectance behavior of gold (Au) in the presence of light with wavelengths ranging from 200 to 1100 nm. The reflectance curve for gold shows several spectral bands of lower reflectance from 200 to 500 nm. This means that in this wavelength range, specular properties of gold objects can be controlled and reduced significantly. This means that if the wavelength of the light source changes from the visible to one on this range during the acquisition of gold objects, it is possible to significantly reduce this reflective effect. So, any wavelength in this rank is useful as an illumination system, for instance, with a wavelength of 480 nm which corresponds to blue (visible band) and which is not dangerous for health. However, as stated we choose as illumination system a UV-A lamp with a wavelength of 350 nm. Even if it could be dangerous, it reduces the level of reflectance in diverse metals like gold, silver or steel, which are materials common in museum pieces.

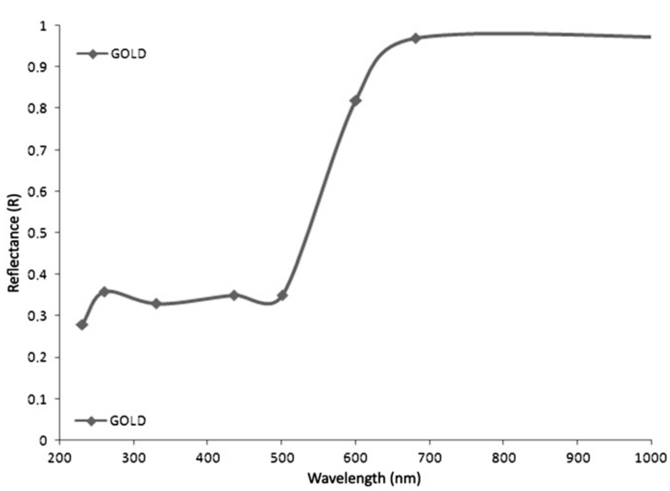

Fig. 1. Reflectance vs wavelength for gold [32].

3.1.2. 3D data acquisition results

The acquisition system: The 3D acquisition system is composed of a commercial 3D scanner (Minolta Vivid 9i), a UV-A lamp of 20 W as the illumination source, and a turntable. This is possible because the Vivid scanner uses the light-stripe method and not a laser where a horizontal light stripe is projected on the object's surface through a cylindrical lens. The reflected light from the object is measured by the CCD sensor and then converted into distance information by applying a triangulation calculation.

The acquisition system geometry was set up as follows: (i) the ambient light conditions are controlled by locating the artifacts in a dark room; (ii) the light sources used (UV-A) were located above the object; (iii) the object is placed on a turntable; and (iv) the object is then digitized using the light-stripe system.

Digitalization process: For each object, three acquisitions were performed with the following conditions: one with white light (standard acquisition), another with UV-A light (proposed acquisition), and the last, once again with white light but, with the object painted with matt white paint (ground truth acquisition). This last condition eliminates reflectivity and provides a reference surface that allowed us to evaluate the precision of the 3D measurement using the UV source. Fig. 2 shows some results for the three acquisitions. The holes and erroneous information in the visible light acquisition compared with the other two acquisitions are obvious. For instance, it is observed in Fig. 2(d) that the Poporo lacks part of the belly; in Fig. 2(e) (the proposed acquisition), this lacking part is present and the acquisition is closer to the ground truth acquisition. One can conclude that the acquisitions using the proposed illumination method produce 3D data that is much closer to the ideal situation where the object is painted.

Fig. 3 shows a reconstruction for gold objects. Reconstruction of a full model of an object using UV-A light requires less 3D data views than with white light. For instance, 13 views are required in order to reconstruct the Jaguar (see Fig. 3(a)) when UV-A light is used, against 18 views when the white light is used. Similarly, in the case of the Poporo (see Fig. 3(b)), the reconstruction with UV-A light required six views against 10 views with white light. In addition, better geometry and smoother data can be measured when the UV-A light is used. This is confirmed by the number of triangles in the resulting mesh. For the Jaguar with UV-A light, 338,386 triangles were obtained against 322,780 triangles using white light. Similarly, for the Poporo, 142,876 triangles were obtained with UV-A light against 120,504 triangles with white light. The differences between the two models are mostly located at the borders of the scanning region and are probably due to specular conditions.

A comparison between reconstructions with the proposed acquisition (using UV-A lighting) and the ground truth acquisition (using the painted object) is performed and shown in Fig. 4. This figure is obtained by registering the two models and measuring the distance between the closest points on each mesh. The color reference on the left of each figure represents the magnitude of the distance (absolute error), being lower in blue and greater in red. One can see that the reconstructed objects using the proposed acquisition technique fit well with an average reconstruction error lower than 100 μm, relative to the reconstruction for the ground truth acquisition.

We believe the reduction in the number of required views is at least as important than the quality of the data and mesh. When the registration process is not automatic, it is necessary to stitch adjacent 3D point clouds for the least number of views which is best.

As results showed, the proposed acquisition system is able to accurately scan specular surfaces such as gold without the use of invasive procedures like painting. This is essential for applications like digitizing cultural heritage objects where no foreign substances

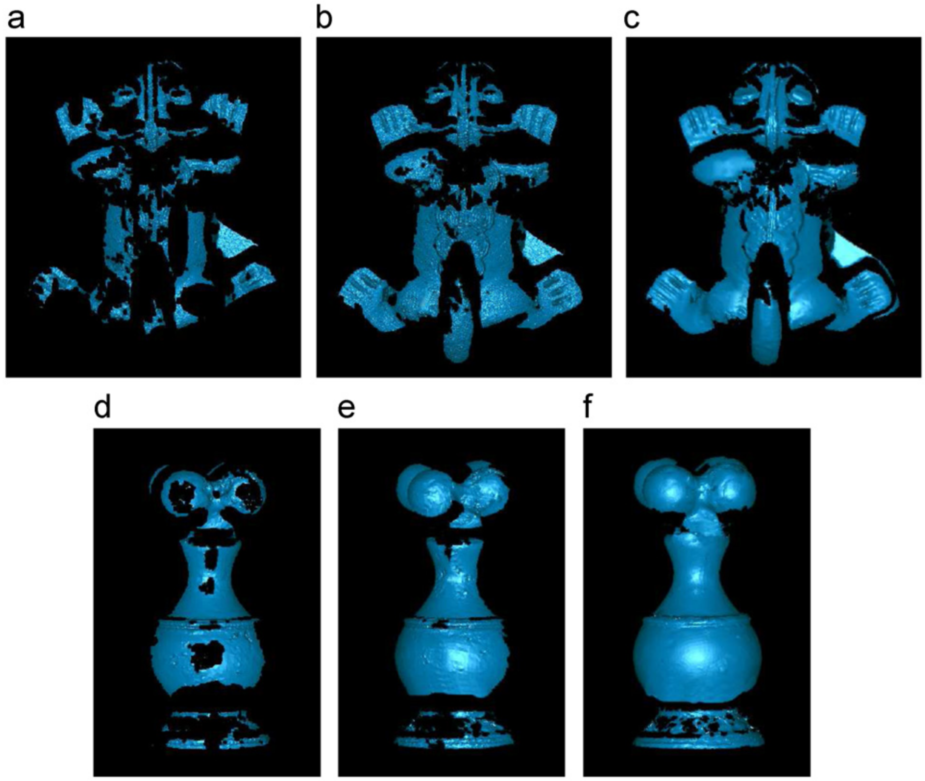

Fig. 2. Range images of the three acquisition methods: (a) white light, (b) UV-A light, (c) painted object, (d) white light, (e) UV-A light and (f) painted object.

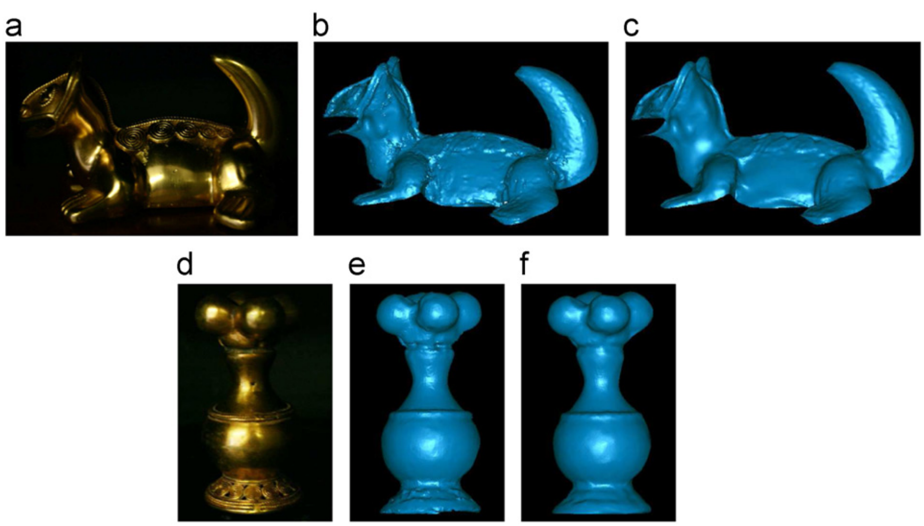

Fig. 3. 3D model of a two gold objects: (a) gold part, (b) white light, (c) UV-A light, (d) gold part, (e) white light and (f) UV-A light.

should touch those precious artifacts. Another important point is that by changing the light source alone, current software and other elements of a 3D scanner do not need to be changed, making this solution simple and cost effective.

4. The multi-modal system

The current version of our multi-modal setup offers visitors to the Gold Museum in Bogotá a unique experience, where they can touch, hear, and see in stereo, six selected pieces. It consists of a stereo display, a haptic device (Sensable's Phantom Omni or Novint's Falcon), and consumer-level speakers, all mounted in a way that co-locates haptic manipulation with stereo visualization. The active stereo display requires shutter glasses, which at first was considered uncomfortable for users. However, due to its higher output quality, we preferred an active display than an auto-stereoscopic one. The haptic device allows visitors to actually touch virtual artifacts, as if visitors had a virtual pen. Small motors apply forces to the physical pen when it approaches virtual surfaces, so users feel as if such a pen and the surface were in contact. This feedback greatly enhances the visual and auditory experience, due to the rich experience it creates and also due to the novelty that it represents for most Museum visitors. Fig. 5 shows our installation at the Museum.

Fig. 6 shows the screen when a user enters the system. It shows small translucent versions of each floor of the Museum with the selected one in red, a big copy of the current floor, and a

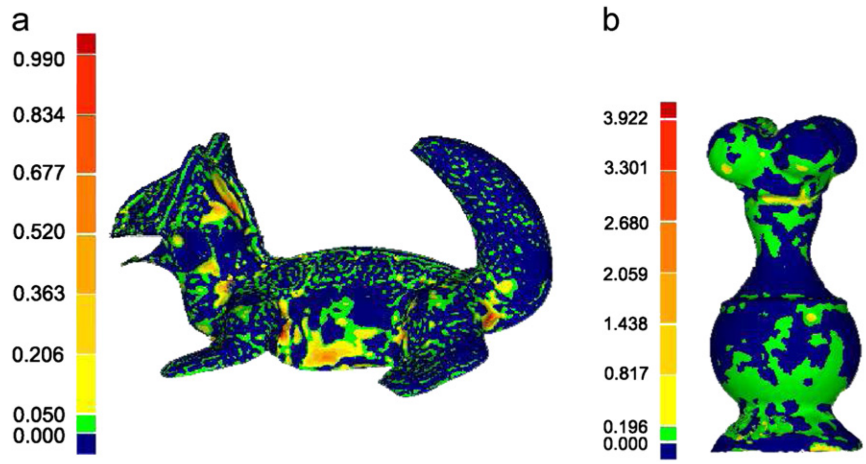

Fig. 4. Comparison of the results between the proposed method and the ground truth: (a) Jaguar artifact and (b) Poporo artifact.

Fig. 5. Multi-modal installation at the Museum.

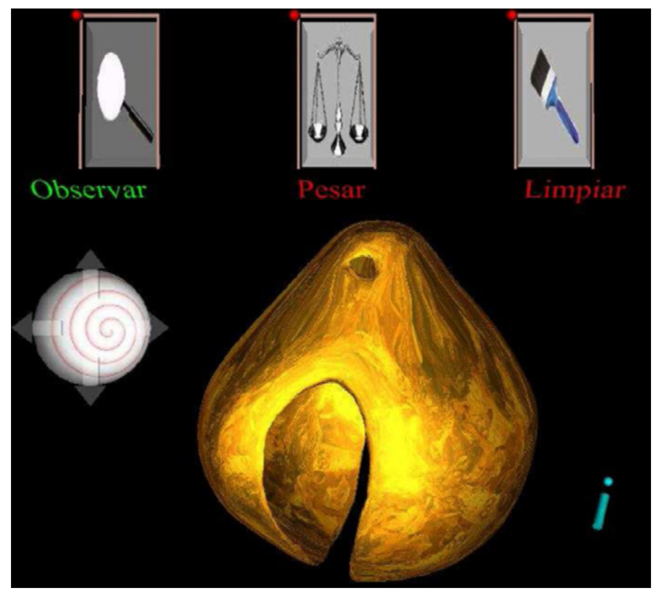

Fig. 7. Observing an object in the haptic installation.

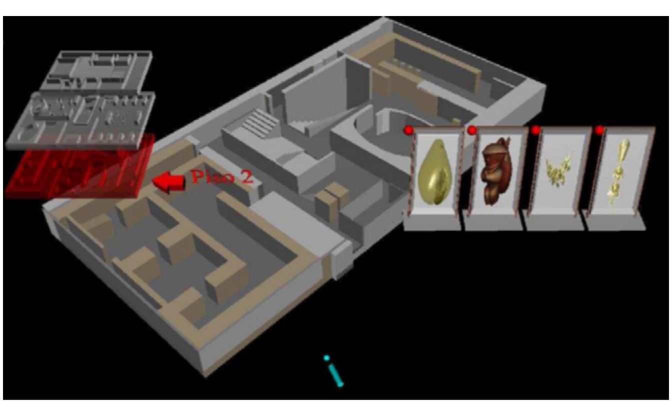

Fig. 6. Entry screen on the haptic installation. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

set of door-like widgets with the virtual approximations that could be visited. The small cylinder with a sphere in its tip represents the haptic pencil. By moving this pencil and touching virtual objects, visitors can change the current floor, so they can see which other objects are available in this virtual exhibition; or they can push one door to see details of a particular object. A door is activated by pushing it in a certain angle, a condition that is shown by changing the color of the door's tip from red to green.

Once a visitor peeks through a door, the system shows a screen such as the one illustrated in Fig. 7, which permits observation of an artifact from a user selected point of view. The sticky white semi-sphere on the left is a widget for rotating the artifact. Once the virtual pen is inside such a widget, it uses the distance from its center to the pen's tip to define a direction of rotation. Visitors can stop rotation by moving the virtual pen to the center of this widget or by leaving its space. This widget allows us to avoid different states in the interface that could appear with the use of buttons in more common techniques such as dragging, so we keep the interface manipulation as simple as possible. It also allows visualization of artifacts without occlusion from the virtual pen. At this level, visitors can touch the artifact and feel its surface and shape. Artifacts can also play sound when hit by the virtual stylus. Options at this level allow visitors to weigh or clean an artifact, and those are represented as doors at the top. The current state is shown with a darker background and other levels with a lighter color.

The weighing mode shows the selected artifact at one side of a simple scale. By pressing the other side of the scale with the haptic pencil, visitors can feel a relative weight of this artifact. We took the weights of all objects in our digitizing installation and we scaled those values to the range available in the device. Although there is evidence that it is not easy for users to distinguish more than three feedback values in simpler haptic devices [34], expert users could feel some differences beyond three levels.

Finally, the cleaning mode is designed to ask visitors to look around an artifact and learn more about the cleaning process that curators perform. Depending on the artifact, we designed two cleaning procedures. In the first one, visitors can see the dirt as stained sections on the artifact. As they rub the artifact with the haptic pencil, it is cleaned. The second procedure shows a recipient full of cleansing liquid below an object and controls that allow visitors to move this object up and down. The section of the object that enters the acid is cleaned.

4.1. Software implementation

We chose H3D [35], an open source API that facilitates the description of a scene, shows stereo output, and facilitates interaction with haptic devices such as the Sensable's Omni and the Novint's Falcon. H3D is designed as an extension of X3D, with extra nodes for handling haptics and behavior. Our application uses a module in H3D that allows us to define the interface as a state machine, depicted in Fig. 8.

Floor selection in the main menu is implemented with the *Switch* X3D node: each time a visitor touches any of the mini maps with the virtual pointer, the system activates a Python script that identifies the selected object, clears the current visualization, and updates the scene graph with the new model. The functionality of pressing a door uses the *DynamicTransform* node. This node allows you to define torque, rotational axis, and an event that triggers a movement of each door, in this case when making contact with the haptics device.

By pushing any of the doors, the state machine changes to the observe state. The rotation widget in this state is a scene that contains a half textured sphere and a *ProximitySensor* node that activates a *ForceField* that keeps the pencil in its proximity. A *SpringEffect* node is added to help locate the haptic device inside the widget. Each time the proximity sensor detects movement within its field, it computes a delta of orientation for the 3D model. The three doors in this scene are governed by the same behavior as the doors of the main scene. Objects are X3D scenes that include a *SmoothSurface* node in order to allow H3D to automatically handle haptic feedback and registration. We manually tuned the parameters of this node in order to create an effect similar to reality.

The weighing state shows a balance that was created in both Blender and X3D code, in order to facilitate the implementation of the balance movement. Each base receives an event interruption once the haptic device makes contact with it, and this event activates a *DynamicTransform* that produces opposite force proportional to the mass defined for each object. We used *RealMass*/100 as the virtual mass for most of our objects in order to use the maximum of the available feedback range, except for the Jaguar and the Ceramic, which used *RealMass*/1000, since their range of weights is much higher in comparison to other objects.

The cleaning state uses a custom node called *PaintableTexture* for objects with two textures: the appearance of the clean artifact and another one for dirt with full opacity. When users touch an artifact, this node receives the texture coordinates and changes the opacity level in the dirt texture to transparent. so the real appearance can be seen. The second method of cleaning uses a similar custom node, *AcidTexture*, that changes opacity according to the level of the object.

We monitor user's activity with a *TimeSensor* node and a Python script that counts 5 s of inactivity before switching to the main state.

4.2. Other installations

In addition to this multi-modal setup, complementary installations were developed. In order to facilitate interaction with high quality images, we created both a web site and multimedia installations.

The web environment is both the basic interactive environment with all captured information and the place for contextual information about this project. A catalog of six virtual reproductions from the 12 artifacts we scanned (Fig. 9) allows users to observe each artifact in detail and hear its sound when they get struck with a virtual stylus. Once a virtual artifact is selected, it is possible to explore its meaning and its origin using the text information, see it from all sides with our Quicktime VR viewer, see it in 3D with a X3D viewer, or see detailed pictures with two Flash-based tools. It is also possible to see the artifact's physical location in the Museum, and the region of Colombia where it was discovered. This exhibition allows us to maximize remote visitors' experience with pictures and textual information. A total of 36 high-resolution pictures allow visitors to observe an artifact at multiple views, and admire its details. The X3D-based reproduction allows exploration from any point-of-view, and to better see an artifact's shape. The web site is available at http://imagine.uniandes.edu.co/MuseoOro.

The multimedia presentation was developed based on the information on the Web. In general, it has the same functionality as the web site, although it is designed to be used in full-screen mode and a rugged track-ball with a button as interface. Fig. 10 shows a detailed view and a magnifying glass view of such an interface. The detailed view is based on high-resolution pictures and the view depends on the distance from the mouse pointer to

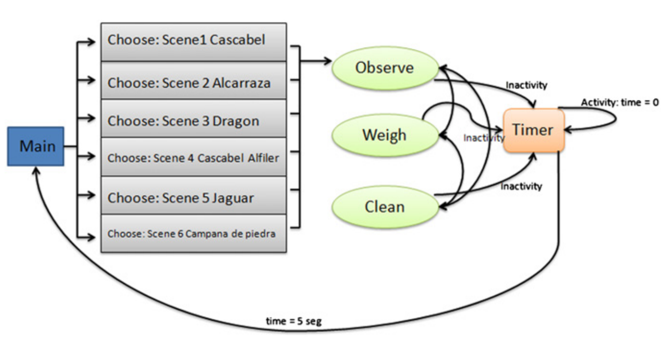

Fig. 8. State machine.

Fig. 9. Web catalog.

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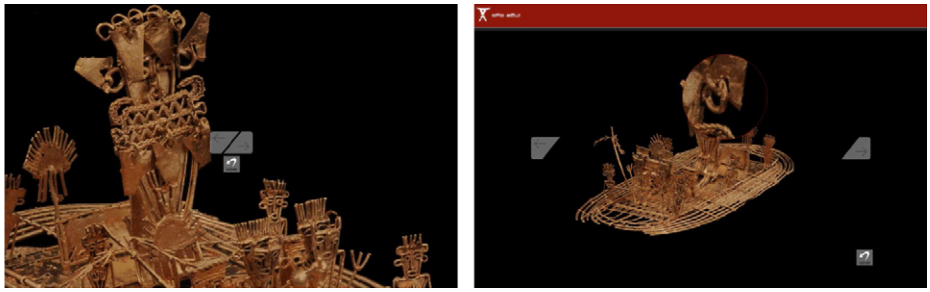

Fig. 10. Detailed view and the magnifying glass view.

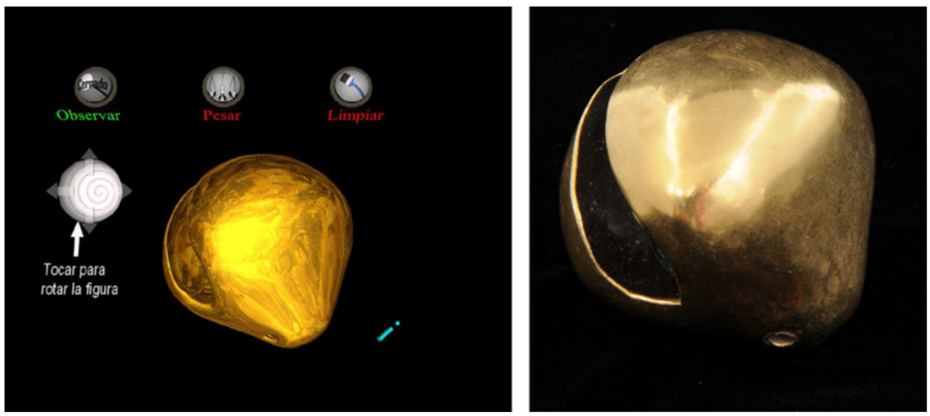

Fig. 11. Comparison between a bell's replica with faked gold material and its picture.

the center of the screen. The magnifying glass view changes the pointer for a circle that shows an enlarged zone in its context.

4.3. Interactive content creation

In terms of content, we captured the shape and the images from six objects of the Museum's collection, with its associated sound for musical artifacts from this set. Our high precision Kreon laser scanner produced models of about 8 Mb and 400,000 polygons per artifact of about 7 cm in length, but we had to reduce the polygon count to about 12,000 polygons in order to allow interactive frame rates for both visual and haptics rendering. Since the laser scanner data did not include textures, we had to rely on hand texturing and fake coloring to finalize the virtual artifact models for this exhibition. Here hand editing means that we have aligned common features in the 3D data with features in the high-resolution photos. In order to do this we have used an algorithm described in Godin et al. [36]. The resulting polygonal model is small but the texture produced by the reduction algorithm preserve the visual complexity of the artifact. Although these methods have been improved in the virtual heritage literature in order to preserve as much detail as possible, our current focus is edutainment and for visitors the achieved quality is satisfactory, as we found in the user studies. In the case of textured pieces, we processed the high-resolution pictures in order to eliminate undesirable shadows from the surroundings and the hardware setup. These pictures were used to create a texture map that allows any viewpoint. In the case of smooth gold pieces it was possible to create a compelling virtual material that looks like the real one with standard OpenGL rendering techniques, such as the gold bell illustrated in Fig. 11.

As we have mentioned, in the case of artifacts with complex textures, it was necessary to manually stitch photographs from the artifacts as textures on the polygons using a photogrammetry technique. This keeps the polygon count low and allows us to show enough detail of an object by using high-resolution texture. We took two sets of 36 high-resolution images around two main axes of each artifact, and we used these photographs in order to create the texture map of each object. Although this process is common in the game industry, it has two main problems that need to be overcome in the future: textures may not perfectly blend due to perspective distortions, and low polygon shapes and standard rendering techniques may show artifacts not present in real-life objects.

4.4. Evaluation and lessons learned

During our iterative development process, we performed several user studies in order to better understand its interactive capabilities, how visitors react to such a system, and to gather information for improvements. Here we present a short overview of the usability studies and their findings. A more detailed analysis can be found in [37].

In our first iteration, we performed an expert evaluation by means of both a directed walk-through and a survey. We showed the users two main hardware setups (with active stereoscopic display and with auto-stereoscopic display) and they were asked to give their opinions. In general, they found the interface very compelling. They liked the weighing experience. They were amazed by the possibilities of auto-stereoscopic displays, although they clearly took more time to adjust their position in front of the auto-stereo display and therefore it was decided to use active stereo for the public version. An issue to be solved in this first version was the lack of detail in certain pieces, since at that time no artifact had textures. We selected the two pieces with most details and we manually added textures to them. Once we had a working prototype, we performed a controlled user evaluation with experts, with a Phantom Omni as the haptic device and two display configurations, one with an active stereo

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display and one with an auto-stereoscopic display. We asked subjects to experience the interface and fill in a questionnaire about their experiences. Although results suggest that the active stereo display was better, the data are not conclusive.

Once we opened the exhibition at the Museum, we decided to perform several observation sessions at different hours, over a period of 20 days in order to better understand how users interact with the system. We have found that although our guide at the display was to play the role of a director more than of coach, it turned out that it was necessary for them to play an active role to teach the visitor how to interact with the system. Visitors lack in general exposure to haptic technologies, and they are either afraid or too enthusiastic about expected feedback. Adult visitors rarely approach the site by themselves, so our guide encourages them to interact, and shows them what to do, what to expect, and what the limits of the system are. Children usually go in groups and they are eager to try our setup, so in this case it is our guide's duty to organize them and control the use of the haptic device since there was only one installation and it was not child-proof. Once visitors interact with the display they are usually amazed by the technology and the virtual exhibition, although they do not express any comment related to the relationship between the real artifact and its virtual approximations. Ambient light is an issue for 3D viewing, and although we have added black covers around the environment, there are pieces that are hardly visible when ambient light is high.

5. Conclusion

In this paper, we present a first attempt at the Gold Museum in Bogota to create a virtual collection of small gold artifacts where visitors can touch, weigh, and explore those artifacts as if they are able to manipulate them. During this project, two new technologies were developed, a 3D data acquisition technique for highly reflective objects using UV-A light and a multi-modal display that gives information through sight, hearing and touch.

The proposed acquisition system uses a commercial 3D scanner with UV-A light sources to acquire 3D data. The UV-A wavelength has the property to reduce the shininess of a gold surface, therefore significantly reducing the specular reflections, and allowing a simple 3D scanner like the Minolta system to digitize those difficult artifacts. With this system, the number of views required for a reconstruction was reduced while the quality of the data stays the same (as with the white light illumination). We confirmed this by comparing the UV-A 3D acquisition of the gold artifact without paint with the white light version with a painted artifact. The difference between the two scans was considered negligible.

Our multi-modal platform integrates information from different sensors and allows visitors to learn and explore, in more detail, high-quality reproductions of small gold artifacts. Users can see the replicas more closely, can touch them with haptic technologies, and can have an experience of the sound they make. Some user evaluations confirm an interest of using this technology in real-world setups. Future work will address more complex representations, which could be also useful for scholars and experts.

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