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ESTABLISHING A DIGITAL 3D IMAGING LABORATORY FOR HERITAGE APPLICATIONS: FIRST TRIALS*

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ABSTRACT

This paper presents the work leading to the launch of a laboratory for digital 3D imaging dedicated to the establishment of a permanent digital heritage preservation centre in Florence. By applying the latest non-contact 3D technologies and methodologies, this center intends to create a bridge between expectations of art historians and curators, and, the people promoting these new 3D technologies. The results of a pilot project aimed at the creation of lasting digital 3D models for archival purpose of statues present in the "Museo dell'Opera del Duomo" in Florence will be described. A summary of experimental results acquired in the fall of 2000 on the "Maddalena" (Donatello) and on a Formella of Andrea Pisano are presented.

1. INTRODUCTION

Non-contact measurement techniques like those based on structured light have found wide spread use in industrial metrology and reverse engineering. Laser-based technologies attempt to structure the environment, through artificial light projection means. The results are dense range maps extracted from visible surfaces that are rather featureless to the naked eye (Rioux 1994). In the field of cultural heritage preservation and diffusion, on-site and complete 3D documentation is necessary in situations where objects and/or environments can't be moved or their access is restricted because of natural causes e.g. earthquake or tourism-related degradation (Taylor 2001). The 3D acquisitions and models will have to be performed in a relatively short time frame. In addition, many applications do not allow any alterations to the object and surroundings to suit the vision system, e.g., by placing markings or changing the reflectivity of the surface with powder or by abrasion. In the last few years, Italy has been a preferred place to carry out 3D imaging and modeling activities in the heritage field. Because of the many world heritage wonders found in Italy and the challenge posed by the diverse settings present in the field of heritage, many teams around the world (and many in Italy) have come here to demonstrate their skills in 3D modeling: (Beraldin 1999, Rushmeier 1999, Levoy 2000).

The NRC of Canada, the University of Florence and the Opera del Duomo in Florence have agreed to carry out a cooperative program in the field of digital three-dimensional (3D) imaging applied to Cultural Heritage. In particular, this cooperation will be concerned first with applications of new 3D sensing technology to the statuary belonging of the City of Florence. Specifically, the following areas will be emphasized:

- Establishment of a permanent heritage preservation centre in Florence that will apply the latest technologies in 3D imaging and modeling;
- Creation of lasting digital 3D models for archival purpose of statues present in the *Museo dell'Opera del Duomo* in Florence.

We have put together a team of people in non-contact 3D imaging and curators (*Museo dell'Opera del Duomo and the Opificio delle Pietre Dure*) that will be in a position to evaluate and use the latest in digital 3D imaging and modeling. The first work of art (see Figure 1) selected is a wood sculpture by Donatello, the Maddalena (circa 1446-1450). This sculpture measures about 180 cm. In order to create a 3D model of this very interesting work of art, a self-contained 3D imaging system was purchased along with the appropriate modeling tools. The second work of art is a bas-relief also known as a *Formella* and was created by Andrea Pisano. In the 3D modeling process, special attention is put on accuracy. Calibrated test objects and verifications through photogrammetric techniques are used. This methodology is critical for obtaining high-quality reconstruction of 3D models from range imagery. This paper presents in section 2 the range camera and the modeling platform used. Section 3 describes the strategy used to evaluate the accuracy of the range images and of the 3D model. Some of the test results obtained so far are shown in section 4. Some of the future directions the team intends to explore are described in section 5. Finally, concluding remarks appear in section 6.

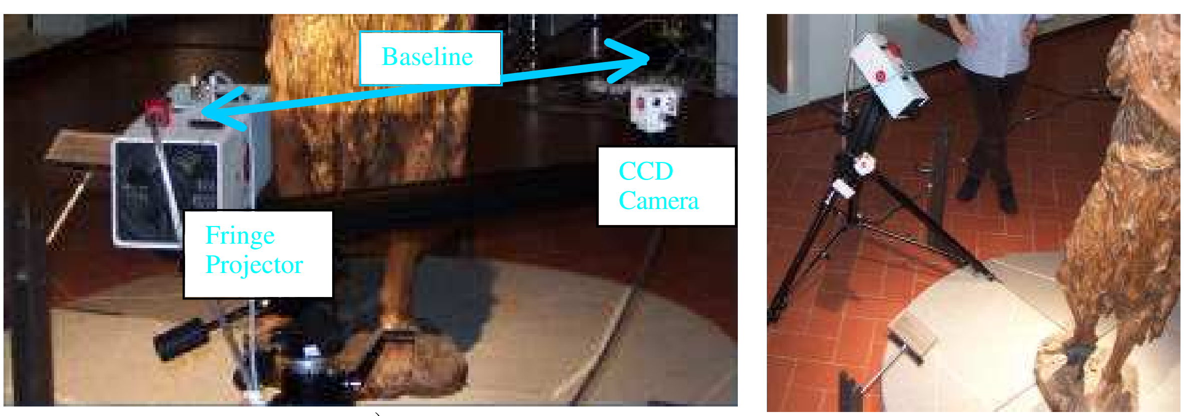
*

a) b) c)

Figure 1 – Maddalena, Donatello (circa 1446-1450): a) side view 1, b) another side view 2, c) frontal view. Height is about 180 cm.

2. COMPACT 3D RANGE CAMERA AND 3D MODELING PLATFORM

In the summer of 2000, a call for tender was sent out and six companies responded with a wide range of 3D imaging systems. The range camera selected and purchased is based on optical triangulation with fringe pattern projection. The system sold by Optonet Srl, of Italy is shown on Figure 2. It was developed to work in museum environments where reliability, robustness, and ease of maintenance are as important as the accuracy. It is capable of satisfying many demanding on-site 3D documentation tasks. The main components of this system are a LCD projector (for pattern projection), a CCD camera, multiple camera lenses (FOV dependent), a variable baseline support beam, and a calibration fixture. Depending on the type of surface imaged (small or large), the field of view and accuracy of the 3D camera are reconfigured. This process allows the team to adapt the modeling process to different situations found in a typical museum. Verification objects are used to check the accuracy of any given measurement session. The accuracy of the final model is assessed using photogrammetric techniques. Similar projection systems are described in the literature (Sansoni 1999) and active 3D systems in general are presented in [Beraldin 2000].



a) b)

Figure 2 – Portable 3D imaging system: a) Triangulation system based upon fringe projection, b) complete system on tripod near the Maddalena at the "Museo dell'Opera del Duomo" in Florence.

The primary goal of the 3D survey is to have an as complete dimensional description of the object as possible. In order to achieve this task, multiple range images are taken at various locations around an object. The views must have enough overlap between them to find the registration and to merge them together. There is no need for artificial aids like targeting. Figure 2 – shows the eighteen images used to create the facial portion of the sculpture. The generation final model is created after the merging process (removal of overlaps) and, optionally, after compressing the polygons to a desired resolution.

Figure 3 – View of the facial features of the sculpture. Here the result of the alignment process of 18 distinct 3D images is shown. Each Image is represented by a colour.

Though the procedure is straightforward, the user must be careful in locating the overlap between images. Surfaces that are quasi-planar or spherical will not align correctly. Two flat surfaces have three degrees of freedom that are not resolvable without resorting to some other constraints.

3. VERIFICATION OF ACCURACY

Though no standard or certification method (accepted internationally) exists to evaluate the accuracy and the measurement uncertainty of range cameras, the user has to devise techniques to ensure a confidence level on what is being measured. Accuracy can be measured with different positions/orientations of the calibration jig (avoid using the same control points) and verifying that it was built with a piece of equipment that is traceable to a known standard. Standards can be classified as international, national, primary, secondary, reference, working, and travelling. Our laboratory collaborates with the Standards group at NRC. This group supplies us with working standards that are sufficient for most of our range cameras. A number of methods are available for the laboratory. Some verification methods can be quite accurate but cumbersome to implement on a site. In practice, an object that is distinct from the calibration equipment and for which the accuracy is ten times better than that of the range camera will be employed in such an evaluation. Unfortunately, it is not easy to bring along an extra object especially if it has to be accurate. For instance, a scale bar made of a stable material with a low thermal dilatation coefficient, e.g., Invar (linear coefficient of 2ppm/ºC) can be used as a compact travelling standard.

As demonstrated by Beraldin 1997, the accuracy of the final 3D model can be assessed with a technique based on a theodolite survey or with what was done here, a photogrammetric survey. The results appear in another paper within this workshop (Guidi et al., 2001). The 3D images shown in this paper were acquired in several configurations depending on the different acquisition phases described in the following section. The calibration uncertainty and the corresponding measurement volumes are reported in table 1.

Tabel 1 – Measurement uncertainties and volumes employed during the scan of the “Maddalena” by Donatello

	σ_x (μm)	σ_y (μm)	σ_z (μm)	Framed Area (mm^2)	Depth (mm)
Initial coarse acquisitions	35	20	125	310 x 230	140
Hole filling step	18	11	75	225 x 165	100
High resolution acquisition	10	6	21	80 x 58	50

Further tests were conducted using a distinct flat plate. A planar surface was fitted to the 3D data in order to estimate the statistics of the measurement uncertainty along the depth axis, i.e. Z axis. The results were similar to those found at the calibration step.

4. RESULTS FROM FIRST TRIALS: FALL 2000

4.1 Maddalena from Donatello

The work on the sculpture by Donatello was divided in 2 separate sessions. The first session that lasted about 30 hours was aimed at acquiring a medium resolution shell with almost all the surface data. The second session was scheduled in order to acquire the higher resolution 3D images that were later superimposed onto the shell. This strategy was selected because of the fact that for a given 3D image resolution, any triangulation-based system will have a limited field of view. When this field of view is too small, then, creating a model from overlapping images becomes tedious and inaccurate. In order to facilitate the modeling and improve the accuracy, a shell is constructed from a camera set-up that provides a large enough field of view. Here one has to make sure that the calibration of the 3D camera is adequate. Numerous tests have been performed at NRC Canada over the years that validate this procedure on closed objects like sculptures using our 3D cameras (Rioux 1994, Beraldin 1999). In any case, we verify the accuracy with photogrammetric techniques that can yield very accurate measurement on feature points. Finally, the higher resolution images are aligned using the software Polyworks with the shell and at the end of the process, the shell is thrown away. Only the high-resolution 3D images remain. To sum up, one has to strike a balance between accuracy, measurement uncertainty, field of view and practicality. Figure 4 and Figure 5 show some results for lower and high resolution images respectively.

a) b) c)

Figure 4 – Maddalena by Donatello, a) photograph of part of the head, b) intensity image captured by our 3D camera, and, c) synthetic shading applied to the 3D image. The lower resolution 3D data are displayed here.

4.2 Reproduction of a Formella from Andrea Pisano located on the bell tower of Giotto.

The reproduction of statuary works and bas-relief is an important aspect of 3D modeling. Because of high levels of air pollution present in densely populated city, curators are now considering replacing original art works with inexpensive copies. These copies can be created from highly accurate 3D models generated with the technique presented in this paper. For centuries, statues have been reproduced by skillful *scalpellini* that mastered the technique based on pantographs. These pantographs are mainly used to verify the correctness of the reproduced surface on some points of interest. Other reproduction techniques are used for bas-relief sculpture like pouring a silicon-based mixture on the work of art and then removing the mold in order to obtain a mold. However these techniques are very hazardous for the work of art. Since its surface can be damaged by direct contact operations.

a) b)

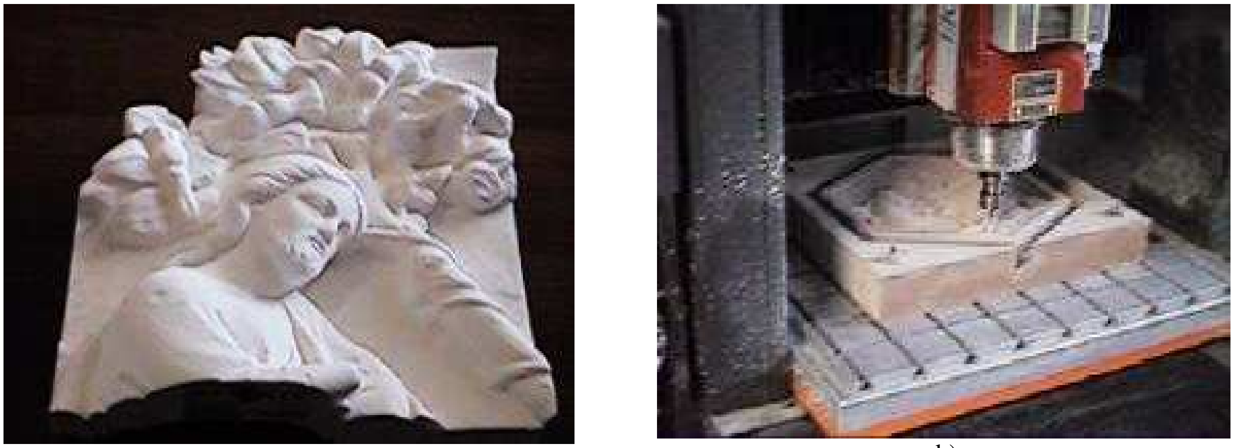
Figure 5 – 3D model of the Maddalena displayed using synthetic shading, a) portion of the face and b) the left eye. The high-resolution 3D data are displayed here.

A demonstrative experiment of the possibility of reproduction of a copy of an art work directly from its digital mold, has been completed using a copy of a formella of Andrea Pisano. The formella represents God who creates Eve from the rib of Adam. The formella was supplied by the Opera del Duomo (see Figure 6a). The original formella was located at the base of the Bell tower of Giotto in Florence. It now resides at the museum of the Opera. Now, a copy stands at its place. The formella has a maximum diagonal of about 87 cm, and it was picked for its intricate surface details.

a) b)

Figure 6 – The formella, a) photograph of the formella as supplied by the Opera del Duomo, b) a view of the digital 3D model using synthetic shading.

The first step was to create the 3D polygonal model. In order to show the surface details, the 3D model is represented on Figure 6b using synthetic shading. The creation of the model required 60 3D images taken from a number of views. The alignment and the merging of the data into a seamless model took about 6 hours. The model is composed of about 2.5 million polygons. From the final model, a section of the formella was picked in order to demonstrate the process of making a copy from a digital model created with a 3D camera. The model is made of nylon (Figure 7a) and was built by stereo-lithography. A second experiment, shown in fig 7b, was performed in order to reproduce the entire formella in a 1:3 scale.



a) b)

Figure 7 The formella, a) a section of the copy made with stereo-lithography, b) scaled model 1:3 manufactured with a milling machine.

5. OTHER APPLICATIONS IN HERITAGE

Museum objects, paintings, archaeological site features, architectural elements and sculpture can be digitized to provide a high-resolution 3D digital record of the object or site. The digital record or “digital model” should provide archival quality documentation which can be used for a variety of research, conservation, archaeological and architectural applications, for fabricating accurate replicas as well as for interactive museum displays and Virtual 3D Theatre applications. This technology can be applied to a variety of museum and heritage applications:

- **Archival Documentation:** tool mark details
- **Museum Exhibition and Display Applications:** interactively examine fine details on 3D digital models using a large screen monitor
- **Research Applications:** magnified, accurately measure, examined under different lighting conditions and display of 3D models with or without colour, e.g. brush stroke on paintings, roll-out photographs
- **Art Conservation Applications:** the data provides an accurate record of the shape, surface condition and colour of an object, which can be used to document and monitor changes at different points in time
- **Archaeological Recording, Architectural & Historic Building, Digitizing Sculpture Applications:** on-site acquisition and modelling
- **Replication Applications:** the object is not touched or damaged during scanning, scale replicas can be made which are much closer or truer representations than those copied by hand, the data can be formatted to machine the replica directly to make a mould
- **3D Virtualized Reality Theatre Applications:** Interactive 3D Virtualized reality systems offer the potential for the “digital repatriation” of models of artefacts, which have been removed to distant museums, back into the virtualized model of their original site.

Though, the current activity has addressed mainly the establishment of a permanent laboratory in Florence and the creation of 3D models. It will soon be extended to cover the area of art conservation. A number of trials are being performed with the principal office for conservation in Florence, i.e. the Opificio delle Pietre Dure.

6. SUMMARY

A 3D imaging system was described along with the platform used to create 3D models. The paper focused on aspects that were optimized to create a system that is portable, accurate and adaptable to museum set-ups. A number of experimental results acquired on a site in Florence Italy were presented. The first work of art selected is a wood sculpture by Donatello, the Maddalena (circa 1446-1450). The second work of art is a bas-relief also known as a Formella by Andrea Pisano. In the 3D modeling process, special attention was put on accuracy. Calibrated test objects and verifications through photogrammetric techniques were used. This methodology is critical for obtaining high-quality reconstruction of 3D models from range imagery. The longer term research goals are to investigate the effect that materials used for sculptures, paintings have on the accuracy of active and passive 3D techniques, define and assess the level of dimensional and photometric accuracy required by museum curators and finally to assess the need for 3D databases.

Other experiments will explore the potential of 3D vision for applications in heritage or as an input to virtualised reality environments. In the case of virtual and virtualised environments, they offer the possibility to expand our abilities in planning, creating and experiencing new surroundings, e.g. virtual tourism on sites that have been closed to the general public. A high degree of realism can be attained by those techniques and the context in which the artifacts were discovered or were used can be recreated. Real world acquisition and modeling is now possible. Technological advances are such that difficulties are more of a logistical nature than technology per se. Many techniques exist to digitize small objects with both a high-resolution 3D surface and a view independent surface texture with perfect registration between them. Models of large objects, structures and environments are possible but we are convinced that the combination of the current technique with other methods that are being explored by our laboratories and others around the world will be required.

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