3D Scanning the Minerva of Arezzo

C. Rocchini, P. Cignoni, C. Montani, P. Pingi, R. Scopigno (*)

R. Fontana, M. Greco, E. Pampaloni, L. Pezzati (#)

M. Cygielman, R. Giachetti, G. Gori, M. Miccio, R. Pecchioli (%)

(*) Istituto Elaborazione dell'Informazione – CNR, Pisa, Italy

E-mail: roberto.scopigno@cnuce.cnr.it

(#) Istituto Nazionale di Ottica Applicata, Firenze, Italy

E-mail: luca@ino.it

(%) Centro di Restauro Archeologico, Firenze, Italy

E-mail: cygielman@virgilio.it

This paper presents the initial results of the "Minerva Project" obtained by means of two different 3D scanning techniques. The Minerva of Arezzo is a bronze statue (Archaeological Museum in Florence) currently under restoration. The "Minerva project" intends to show how 3D techniques can integrate standard diagnostic methods giving useful and powerful tools to the restorers. The main goal of the project is to build complete 3D digital models of the Minerva statue, before, during and after restoration in order to monitor the various phases of the restoration process. The case study is very stimulating, because variations of the shape (removal of plaster, polishing of the corroded bronze surface) and of the colour (removal of the thick paint film on the bronze surface) of the statue are forecasted. In this work we also discuss the experience we get and the problems encountered during the project.

KEYWORDS: digital models, 3D scanning, computer graphics, computed-aided restoration, virtual reality.

INTRODUCTION

This paper reports the first results of an in-progress joint project concerning the development and use of new 3D graphic technologies in the Cultural Heritage (CH) field, specifically oriented to restoration needs and constraints. The restoration of a bronze statue of great historical-artistic interest, the Minerva of Arezzo, gave us the opportunity for testing these technologies.

3D digital models have a wide application field: realization of 3D catalogues and virtual museum, fast prototyping, supporting the restoration project, etc. All these applications require a *3D model*, that is the digital representation of the object involved. Classic 3D modeling tools are often inadequate to reproduce the complex shape of most art works (e.g. sculptures) whereas 3D scanning techniques are sufficiently accurate to provide a high fidelity reproduction of the shape of an object. These techniques have been adopted in a number of recent Cultural Heritage projects, e.g.: the Digital Michelangelo Project of the Stanford University [8], the acquisition of Michelangelo's Pietà in Florence by the IBM T.J. Watson Laboratory [13], and the acquisition of a section of the Coliseum in Rome by an Italian research team [5]. 3D scanning technology evolved in the last few years, but its use in many CH applications has been hampered because of the high cost of 3D scanning devices, the limited diffusion of knowledge about its potentialities and the fact that only few applications are able to manage 3D complex models, thus showing the full capabilities of such data.

The Minerva project goal is therefore to further develop and assess 3D scanning and graphic technologies, with a particular focus on the art works restoration. We also aim to set up a multidisciplinary team of experts in restoration, archaeology, optics and computer science in order to design useful new tools for the restorers.

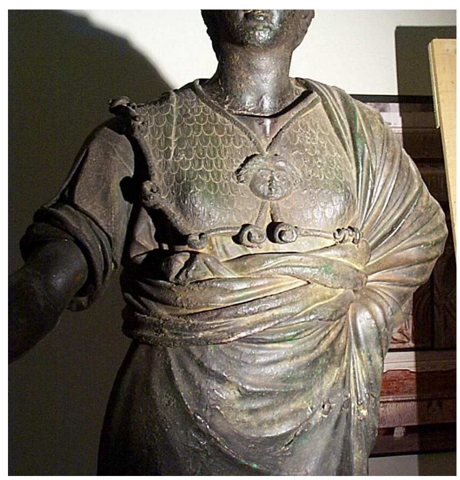

Figure 1: The Minerva of Arezzo (part of).

THE RESTORATION OF THE MINERVA OF AREZZO

The "Minerva of Arezzo" is a bronze statue discovered in Arezzo in 1541 (see Figure 1) whose origin is still uncertain: it could be either an original Hellenistic bronze dating back to third century B.C., or a variant produced in the Roman Imperial period (first century A.D.). The statue is usually located in the Archaeological Museum in Florence, and is now under restoration at the Archaeological Restoration Centre in Florence. The restoration was considered very urgent because of the highly endangered status of the statue (precarious conditions of the structural wooden elements inside the statue, extensive corrosion of the bronze layer). Besides that, the statue was extensively restored in the past (the main restorations dates back to the sixteenth and the eighteenth centuries), and these actions modified in a significant manner the aspect and integrity of the artwork. As an example, a missing arm (the right one) was replaced in the eighteenth century restoration; plaster was used to join disconnected bronze sections and to fill gaps; finally, a dark greenish paint covers most of the statue surface, giving a uniform aspect to the plaster and the bronze sections but actually covering the original patina. This restoration is very complex because of the heterogeneity of the component materials, so the following actions were planned: the realization of a physical reproduction of the Minerva by casting the statue; an accurate analysis of the statue conditions (performed via: visual inspection; a photographic survey under visible and UV light; an X-ray imaging survey); an accurate clean up of the statue surface, to remove dust and dirty deposits; the removal of the plaster fillings (made by gypsum or glue) and the endangered internal wooden support followed by its replacement with a new structural frame; an accurate polishing of the bronze surface either by mechanical removal of the bronze oxidation or by the use of other innovative technology such as laser-based polishing instruments; finally, the re-assembly of the statue components with techniques and materials more adequate than the ones used in the previous restorations.

The acquisition of a complete digital model of the statue is considered of primary importance for monitoring its status before and after the restoration. Therefore the accuracy of the digital model has to be sufficient to reveal alterations of the statue's shape due to restoration, (e.g. the removal of the plaster fillings or non-original elements); the surface colour alteration due to the removal of the paint film and the metal polishing has to be acquired and all the collected data have to be organised for an easy and interactive visualization, manipulation and analysis on low-cost computers (PC's).

3D SCANNING TECHNOLOGIES DEVELOPED

The Minerva Project gives us the possibility to evaluate and compare two different hardware technologies (a 3D scanner based on structured light and a laser scanner) and to test a suite of software tools for the management of 3D scanning data. Let us describe the characteristics of these components in the following subsections.

A low cost scanner based on structured light

An optical scanner is generally based on a couple of devices: an *emitter*, which projects structured light on the object to be scanned, and a *sensor*, which acquires images of the distorted pattern reflected by the object surface. The 3D geometry is reconstructed by triangulation, given a known location of the emitter-sensor pair.
The scanner developed by C.N.R. [11] has been designed using only consumer technology, thus ensuring affordable hardware costs and enabling easy technological improvements. The accuracy and resolution supported are midway between commercial low cost and high quality laser scanners . The instrument supports the surface color acquisition referred to the statue geometry and ensures easy operability and flexibility.

Figure 2: The low cost scanner designed by CNR (Pisa), based on structured light and consumer electronic technology.

In our scanner the emitter is a video projector (DLP technology) and the sensor is a digital still camera. The advantage of using a video projector to produce a structured light pattern is that we can easily experiment and evaluate different patterns. One possibility is to produce an image with a set of thin and tightly packed vertical bands, but this solution gives some problems with objects having a complex topology: the presence of self-occluded parts might cause some bands to disappear or brake, and this makes the reconstruction of band indexing not feasible. The use of a hierarchical pattern where the band spatial frequency is iteratively doubled (binary coded illumination), can solve this problem [7]. Our system uses this approach. A set of colored band pattern is produced by dividing, at every step, each region in two sub-regions, red on the left and blue on the right, separated by a green line (see an example of the recursive process in Figure 3). These images are produced recursively until we reach the projector resolution.
Stripe detection and indexing is implemented using a progressive approach: the new stripes introduced in image *k* are recognized and reconstructed on the base of the knowledge acquired reconstructing images [*1,..k-1*].
A software module running on a standard PC drives the emitter and the sensor devices. Photos are taken to acquire images either of the distorted patterns (from which the geometry is reconstructed by triangulation, producing a range map) or of the object under different illumination conditions (from which the illumination-invariant color, or "albedo", of the object surface is reconstructed). The color images are by definition self-registered with range maps.

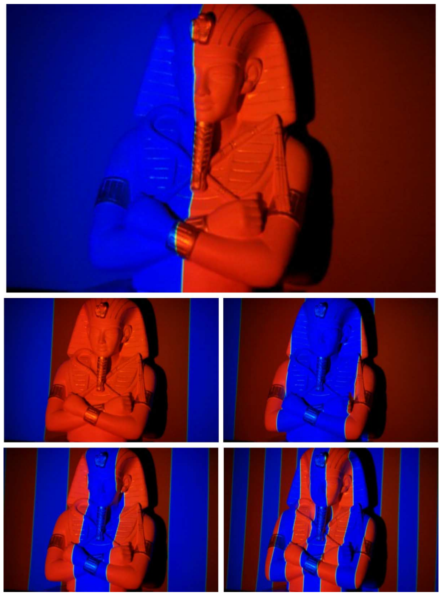

Figure 3: The set of coloured stripe images projected on the surface of the object.

The scanning system, depicted in Figure 2, produces:

- a range map of each selected surface portion, with sample density of approximately 0.7 mm on the vertical axis and 1.4 mm on the horizontal one (using a 1024×768 video projector, located at approximately 1.3 m. from the work of art);
- an illumination-invariant color texture which represents the pictorial detail present on the acquired surface section, reconstructed adopting a technique proposed in [14].

As usual in 3D scanning, complex objects are modeled via the acquisition of a set of partially overlapping range scans. Our proprietary software is used to register and merge all the range maps in a single triangulated mesh, and is described briefly in a following section.

The laser scanner

A laser scanner for Cultural Heritage applications has been realized at the Istituto Nazionale di Ottica Applicata (INOA) in Florence. Among the active non-contact devices for 3D measurements, laser scanner is probably the most versatile one. Its main advantages are great set-up simplicity, small size and high resolution.

The working principle is based on the optical triangulation: a light source illuminates an object and an image of this light spot is then formed, by means of a lens, on the surface of a linear light sensitive sensor. By measuring the location of the light spot image the distance of the object from the instrument can be determined, provided the baseline and the angles are known [8] .

Figure 4: Experimental setup of the prototype of laser scanner designed by INOA (Florence).

Figure 5: A plaster head with the superposition of the red laser line.

The source employed is a laser diode (Lasiris Inc., $\lambda = 670$ nm, $P = 30$ mW) with a 60° prism head to project a light line, and the sensor is a CCD camera (Jaj Corp., 1300×1030 square pixel 6.7 µm wide, S/N > 56 dB). These two devices are mounted on a motorized stage to allow the scanning of statues or architectural moldings, and the whole system is computer controlled. The experimental setup is shown in Figure 4. In its typical configuration, the laser sheet is horizontal (parallel to the floor), but to facilitate scanning horizontal crevices and extruded parts, the system can be oriented anyhow. The gantry consists of two vertical trusses (2 meter long) on which the motorized stage can vertically translate and rotate around an axis perpendicular to them.

The system has been tested on reference surfaces and corrections for lens distortion were made. The accuracy of location of the image spot, and hence the instrument accuracy, is degraded by laser speckle [1]. The resulting quota resolution is 50 µm and the absolute error is less

than 300 μm, with a standoff distance of 50 cm and a scanned area of about 40×40 cm^2.
The control software, realized at INOA, manages both the control (translation stage) and the acquisition systems (grabber and CCD camera). The output is a sequence of profiles gathered in meshes of binary data, i.e. the initial range maps.
The following processing consists of aligning and merging the scans taken from different gantry positions (see following paragraph).

Software tools for 3D scanning

The pipeline of phases of any 3D scanning session is rather complex, involving many steps: **scanning** the object; **aligning** the range maps (that have to lie in the same space); range map **merging** (to build a single, non redundant mesh out of the many, partially overlapping range maps); mesh **editing** (to improve the quality of the reconstructed mesh); mesh **simplification** (to reduce the often huge complexity of the model obtained); finally, mesh **conversion** (to export the mesh produced to the data representation scheme of interest). A comprehensive tutorial of the techniques proposed in literature and most frequently used in applications has been recently proposed in [2]. The CNR project partner has designed a suite of software tools that manages most of these phases:

- **MESHALIGN**: the module allows the registration of multiple range maps (needed to get a complete coverage of the object surface), which by definition represent the distance of the sampled surface points from the sensor location. This means that all these range maps have to be transformed into a unique reference space, such that sections of the range maps that correspond to the same surface zone will overlap. The registration module follows the approach proposed in [9], improved by the adoption of a multiple level of detail representation of the range maps which allows better performances and higher process accuracy.
- **MESHMERGE**: the module allows the reconstruction of a single 3D mesh out of a set of registered range maps. It adopts a new approach [10], which is characterized by a lower space complexity and improved accuracy with respect to the current alternative volumetric reconstruction approaches [4].
- **MESHEDIT**: the module allows performing simple editing actions on the mesh, to improve its quality (e.g. to fill small holes, to remove non-manifold components of dangling edges/faces, to apply smoothing filters, etc).
- **MESHSIMPLIFY**: the module supports the simplification of the [huge] meshes produced by 3D scanning devices, by removing in a controlled manner mesh vertices. The simplification follows the edge collapse approach [6] and has been implemented in an *out-of-core* fashion to allow the management of meshes that could be larger than the core memory of the computer used [3].

RESULTS

The Minerva statue has been scanned using both the two scanner devices presented. In the case of the first scanner (structured light) we took 146 range maps. For each range map we shot: one image of the object under white light plus 10 images to get all the stripe patterns; 6 images for the acquisition of the colour (six different lighting conditions). In total we have 17 images for each range map (shape + colour).
The Minerva has been scanned with the help of a rotating platform. The scanner was positioned at approximately 1.3 meters from the statue, and each range map sampled a section wide approximately 70 cm×50 cm. For each complete rotation of the statue we get 12 range maps, and after completing this piece-wise pseudo-cylindrical scan we raised the height of the scanner to acquire the next section. Due to the required overlap of the range maps, we acquired 8 of these pseudo-cylindrical scans (getting in total 96 range maps). Some more range maps were taken to get some sections of the Minerva surface that were not represented in the previous ones with sufficient accuracy or completeness (e.g. the right protruding arm, the neck, the top of the head, etc). The images shot were around 2,500 for approximately 1,2 GB on disk.
Our software has been used to register and merge all the range maps in a single triangulated mesh. The alignment of this complex set of range maps took approximately 4 weeks (but it is hard to estimate the effective time, because during the aligning session we also spent time to discover bugs or to refine the user interface and the functionalities of the MESHALIGN tool). A complete digital model of the Minerva has been produced, and is shown in Figure 6. The 3D mesh has been reconstructed from the range maps using MESHMERGE and selecting an inter-voxel distance of 0.57 mm. The mesh reconstructed is rather big: 26 millions of triangular faces. To improve usability, this mesh was simplified using our external memory simplifier, MESHSIMPLIFY. The results presented in Figure 6 are simplified models representing the whole statue (with around 1M faces) and the head section (with around 1.1M faces).
The acquisition of the color has given us some problems because our approach assumes a Lambertian reflection model [14, 12]. Conversely, the bronze surface is not Lambertian but highly reflective. For this reason the un-shaded albedo colors returned by our original approach are not completely satisfactory, and we are designing a different approach to cope with this issue.
Further actions planned are the integration of the laser-scanned model with the color data that have been sampled with the structured light scanner and another acquisition of the statue after the restoration.

Figure 6: Digital 3D models of the Minerva's head and full body.

CONCLUSIONS

We have presented the preliminary results of the "Minerva Project", aimed to develop and evaluate 3D scanning technologies in the Cultural Heritage field. A multidisciplinary team has been formed to approach the problems, validate the technologies chosen and interpret the experimental results. A structured-light scanner, a laser scanner and a suite of software tools for the management of 3D scanned data were experimented on the Minerva of Arezzo to realize a digital model of the statue. The work done up to now is mainly technology-push. Next steps will be to foster these technologies, and to develop specific applications oriented to meet the restoration needs.

Acknowledgements

We acknowledge the financial support of the Progetto Finalizzato "Beni Culturali" (Italian National Research Council) and of the Progetto "RIS+" (Tuscany Regional Government).

BIBLIOGRAPHY

1. R. Baribeau, M. Rioux. *Influence of speckle on laser range finders,* Appl. Opt. Vol. 30, No. 20, July 1991.

2. F. Bernardini, H. Rushmeier, *The 3D Model Acquisition Pipeline*, STAR Proceedings, Eurographics 2000 Conference, pp.41-62.

3. P. Cignoni, C. Montani, C. Rocchini, R. Scopigno, *External Memory Management and Simplification of Huge Meshes*, IEI-CNR Tech. Rep., submitted paper, Jan. 2001, pp.10.

4. B. Curless, M. Levoy, *A volumetric method for building complex models from range images*, In SIGGRAPH '96 Proceedings, ACM SIGGRAPH, 1996, pp. 303-312.

5. M. Gaiani,M. Balzani,and F. Uccelli, *Reshaping the Coliseum in Rome*, Computer Graphics Forum, Vol. 19(3),2000, pages 369-378.

6. M. Garland and P.S. Heckbert, *Surface simplification using quadric error metrics*, In SIGGRAPH 97 Conference Proceedings, ACM SIGGRAPH, 1997, pages 209 –216.

7. S. Inokuchi, K. Sato, F. Matsuda, *Range-imaging system for 3D object recognition*, Int. Conf. On Pattern Recognition, Montreal, Canada, 1984, pp.806-808.

8. M. Levoy, K. Pulli, B. Curless, S. Rusinkiewicz, et.al., *The Digital Michelangelo Project: 3D scanning of large statues*, In Comp. Graph. Proc., Annual Conf. Series (Siggraph '00), Addison Wesley, July 24-28 2000, pages 131 –144.

9. K. Pulli, *Multiview registration for large datasets*, Proc Second Int. Conf. on 3D Digital Imaging and Modeling, , Ottawa, Canada, October 1999,pp.160-168.

10. C. Rocchini, P. Cignoni, C. Montani, R. Scopigno, *The Marching Intersections Algorithm for merging range images*, IEI-CNR Tech. Rep., submitted paper, July 2000.

11. C. Rocchini, P. Cignoni, C. Montani, R, Scopigno, *A low cost optical 3D scanner*, Computer Graphics Forum, Vol. 20(3),2001, (in press).

12. C. Rocchini, P. Cignoni, C. Montani and R. Scopigno, *Multiple Textures Stitching and Blending on 3D Objects*, Rendering Techniques ''99, Springer Wien, 1999, pp. 119--130.

13. H. Rushmeier, F. Bernardini, J. Mittleman, G. Taubin, *Acquiring input for rendering at appropriate levels of detail: digitizing a Pieta*, Eurographics Rendering Workshop 1998, G. Drettakis and N. Max (ed.), Springer Wien, 1998.

14. H. Rushmeier and F. Bernardini, *Computing consistent normals and colors from photometric data*, in Proc. of the 2nd Intl. Conf. on 3-D Digital Imaging and Modeling, Ottawa, Canada, October 1999, pp. 99–108.