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TRIDIMENSIONAL DIGITIZING OF DONATELLO'S MADDALENA

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ABSTRACT

3D optical scanning technologies for measuring tridimensional shapes of sculptures have emerged in the last few years as the most promising methods for digital analysis and preservation of Cultural Heritage. This paper presents the work leading to the generation of the digital 3D model of Donatello's *Maddalena*, kept in the museum of the Opera del Duomo in Florence. The acquisitions have been taken with a system based on fringe projection. The metric reliability of *Maddalena*'s tridimensional model, obtained through iterative alignments of single 3D acquisitions, has been also verified through a well established technique such as photogrammetry. A set of point-to-point distances evaluated with both methods has been compared and discussed in order to estimate the overall accuracy of the final model.

1. INTRODUCTION

Non-contact measurement techniques like those based on laser or structured light projection have found wide spread use in industrial metrology and reverse engineering.

In the field of Cultural Heritage 3D numerical models can find several applications such as digital cataloguing of the artistic patrimony, verification of the state of conservation of an artwork, simulation of possible restoration work, documentation of previous restorations, making of moulds and replicas [1].

In the last few years, several international and italian teams have worked on italian Heritage to demonstrate the maturity of 3D modeling [2, 3, 4] for these applications. Recently, the University of Florence, NRC of Canada, and the Opera del Duomo in Florence have agreed to carry out a cooperative program in the field of digital tridimensional imaging applied to Cultural Heritage. In particular, this cooperation will be concerned with application of new 3D sensing technology to the statuary kept in the Museum of the Opera del Duomo in Florence.

We have put together a team of people expert in non-contact imaging that will be in a position to use and evaluate the latest in digital 3D imaging and modeling for application to Heritage. The first work of art selected for scanning is the *Maddalena* by Donatello (circa 1455), a wood sculpture about 190 cm tall.

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.

2. RANGE CAMERA

The system employed to obtain the results described in this paper was a commercial scanner (Opto3D Ranger, Optonet Srl, Brescia , Italy) especially designed 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. It uses a 3D measurement method based on structured light. This technique, based on optical triangulation, makes use of the projection of various fringe patterns over the measurement area, according to a given sequence, and their acquisition from one television camera angled with respect to the projection direction. The deformation of the pattern acquired, after a proper processing, allows gaining one cloud of 3D points reproducing the shape of the illuminated object [1].

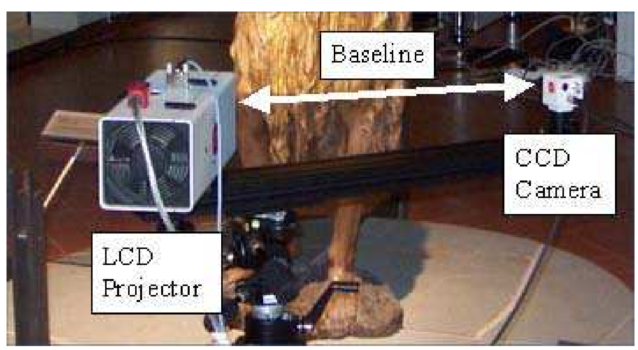


Figure 1 – Range camera used for digitizing Donatello's *Maddalena*

The main components of the 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, as shown in fig. 1. 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 modeling process to be adapted to different situations found in a museum. Test objects are used to check the accuracy of any given measurement session.

By relocating the optical head with respect to the object it is possible to measure various sights, until all the visible surface of the object is covered. 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.

3. MODELING PLATFORM

In order to obtain the complete model, the operation of alignment and fusion of 3D images can be carried out by a variety of software techniques commercially available. In our case, the software Polyworks™ (Innovmetric, Québec- Canada) was used. It employs one of the various point clouds as starting reference, and performs a roto-translation of each adjacent image in order to be aligned to the reference. The procedure is repeated iteratively until all the images from various points of view are properly aligned. The following phase is the merge of all aligned point clouds; the duplicated points in the superposition areas between adjacent images are averaged. From the resulting point cloud a triangular mesh representing the measured surface is then generated.

4. CREATION OF THE 3D MODEL

The acquisition work on the sculpture was divided in two separate sessions. The first session, that lasted about 30 hours, was aimed at acquiring a medium resolution (125 μm) shell with almost all the surface data. The second session was scheduled in order to acquire the higher resolution (about 75 μm) 3D images that were later superimposed on 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, 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. Since in this way we used almost half the spatial resolution, we roughly reduced of four times the number of images necessary for obtaining a closed model (even if not complete), reducing in this way the error propagation.

The scanning process led in this phase at the acquisition and alignment of about 150 images organized in horizontal strips running around the statue.

a) b) c)

Figure 2 – Donatello's *Maddalena* : a) Photo of the sculpture; b and c) synthetically shaded digital model.

Finally, the higher resolution images were aligned with the shell using the software Polyworks™ , and at the end of the process the shell is thrown away. Only the high-resolution 3D images remain.

Figure 3 – Donatello's *Maddalena* 3D model: face details.

5. QUALITY CONTROL ON THE MODEL

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. Some techniques 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 must be employed in such an evaluation.

As demonstrated by Beraldin [6], the accuracy of the final 3D model can be assessed with a technique based on a theodolite survey. In our case a photogrammetric survey was adopted in order to make quality control over specific points of the statue.

The use of photogrammetry in this context has not led to restitution , but has been finalised only toward examining and verifying models obtained using optical scanning. In the survey project the lowest number of photographs possible to frame the entire sculpture was taken, remaining within a good range of accuracy thanks to a base-distance ratio of about 1:3.

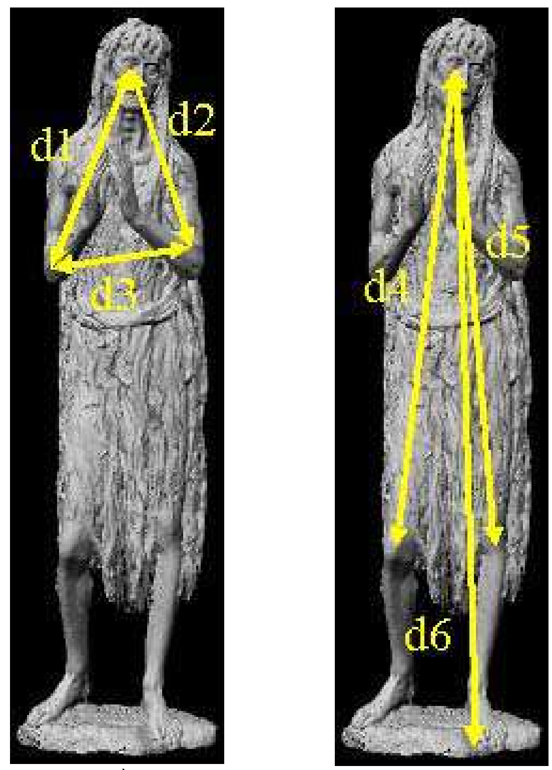
The experiments performed with both techniques gave two set of measurements defined in a couple of reference systems different between each other. Therefore, in order to avoid the problem of aligning them, we chose to measure some distances between points clearly recognizable on both the 3D images and the metric photographs, employing as targets features present on the statue's surface such as wood-worm holes.

As the photogrammetric system used in this case was based on manual collimation, we tried to reduce the operator selection error employing 3D scans at resolution higher than that used for the model. In such way the framed area associated to each 3D scan resulted similar to that targeted by the collimation system on the metric images at the maximum optical zoom.

Since raw 3D images have their own reference system, unrelated to the one of the whole model, we aligned each high-resolution point cloud on the "skeleton" model through the Polyworks^{TM} software, producing in this way a roto-translation matrix for each aligned image, which allowed to map the spatial coordinates of the raw image in a common reference system for the whole model.

We developed a specific piece of software to operate a pixel selection on the bitmap image associated to the point cloud, which stores the 3D coordinates and transfers them in the reference system of the model, producing also a bitmap file with a well visible target superimposed on the gray levels image. Once a couple of raw points has been selected (even from different 3D acquisitions), the same software calculates the distance between them in the model reference system. A couple of "stamped" images are then passed to the photogrammetry operator for the following manual selection of the corresponding points.

A possible critical aspect in the comparison of the two measurement methods is the operator error made during selection of points. For this reason we performed several subsequent distance measurements between two points at the opposite ends of the statue with both methods, obtaining a standard deviation of 0.074 mm with the 3D approach, and 0.266 mm with photogrammetry. Since the deviations obtained are limited, we decided to avoid repeated measurements on each test point considering that every data collected may intrinsically be affected by such uncertainty.



a) b)

Figure 4 – Distances surveyed by photogrammetry and 3D scanning: a) results in good agreement; b) results with higher differences

Some distances measured through the two systems, fully reported in another paper [7], are described in figure 4 and reported in table 1. Few of them have been repeated and averaged for few points near each other when the selection feature was ambiguous or badly defined.

The deviations between photogrammetry and 3D model reported in the fourth column of table 1 (Δ) have been categorized according to their value. All the deviations below three times the standard deviation of the most inaccurate method (0.226 mm) have been considered equal; they have been shown in figure 4a and grouped in the first lines of the table. This shows that the distance between points belonging to the bust, as the distance between the right eye and the arms (d1 and d2), or the distance between arms (d3), have very similar values with both measurement techniques. Such agreement is supposed to be due to a good alignment that was possible thanks to reliable scans as those related with the upper part of the statue, where several well-defined features are present, and the surfaces are mainly convex and with few discontinuities. Hence the related point clouds have no significant gaps. The partial horizontal alignments leading to the upper part of the model, described as "strips" in section 4, are therefore accurate, and permit a good positioning also along the vertical direction.

	Photogrammetry (mm)	3D model (mm)	Δ (mm)
d1	467.5	467.9	-0.4
d2	470.8	470.6	0.2
d3	269.0	268.7	0.3
d4	1170.9	1169.4	1.5
d5	1198.4	1194.0	4.4
d6	1677.9	1674.0	3.9

Table 1 - Comparison of distances between specific points measured by photogrammetry and over the 3D model.

Conversely, the typical discontinuous surface of the lower part of the statue led to fragmented scans, whose alignment was more complex and involved wider errors. This is confirmed by the measurements from the right eye and the knees and the left foot (d4, d5 and d6 highlighted in fig. 4b), that emphasize a compression of the 3D model with respect to the photogrammetric survey.

In conclusion, the photogrammetric model has been used as a reference for the 3D model thanks to its better overall accuracy, and allowed to detect small dimensional deviations of the final 3D model due to alignment errors.

On the other hand the high local accuracy attainable with the optical 3D scanning (much better than the one attainable with photogrammetry) seems to be sufficient to maintain a reasonable overall accuracy over the whole model when the scan involves uninterrupted surfaces.

When highly complex surfaces have to be acquired, however, the lack of points due to shadows and other physical constrains may give worst alignment with significant dimensional errors.

6. CONCLUSIONS

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. The experimental results obtained on the *Maddalena*, a wood sculpture by Donatello, acquired on a site in Florence, Italy, have been presented. In the 3D modeling process, special attention was put on accuracy. Calibrated test objects and verifications through photogrammetric techniques were used. These evidenced that in some situations, as for example when surfaces extremely fragmented have to be reconstructed, software alignment of tridimensional images might be critical for obtaining high-quality 3D models. In those cases, an integration of the two different techniques appears to be a proper approach for a correct data registration.

7. ACKNOWLEDGMENTS

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