RAPID MANUFACTURING OF SCULPTURES REPLICAS: A COMPARISON BETWEEN 3D OPTICAL SCANNERS

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ABSTRACT

In recent times emergent time-compression technologies have extended their application field to the artistic-archaeological sector. Such expansion has been consolidated by the introduction and the development of non-contact optical digitisers, which are faster and less invasive than contact scanning devices. Free-form complex surfaces, typical of artistic sculptures, make contact digitising quite expensive in terms of time. Sometimes scanning may be even impossible from an operational point of view. In this paper two optical scanning devices, operating by different principles (laser triangulation and structured light), are compared. A scaled replica of Michelangelo's David has been selected as benchmark. Different criteria of comparison are employed to choose which digitiser is the best for the selected case study. The evaluation is not limited to the comparison between the reconstructed virtual models of Michelangelo's David. Through the integration between Reverse Engineering and Rapid Prototyping, in fact, two copies of the sculpture have been produced, one for each reconstructed model, by the 3D Printing technology. The scanning device, which resulted to better fit for the chosen application, was then employed to scan another Michelangelo's sculptural masterpiece: the Moses.

1. INTRODUCTION

In the latest years Reverse Engineering technologies have been applied outside the industrial field. A great number of works and scientific papers, concerning the digitisation of forms in the archaeological and artistic sector, is available in technical literature (Boelher, 2000; Fangi 2001; Iuliano, 2002).
In the field of the preservation of art objects and cultural heritage the reconstruction of a virtual three-dimensional model of artworks has several purposes. Reverse Engineering is generally applied on buildings and sculptures of great dimensions, nevertheless applications on small artworks were considered as well (Boelher, 2000; Iuliano, 1999). Such artefacts, in fact, deteriorate with the passing of time anyway, even when they are not directly exposed to atmospheric agents.
Storing a digital copy of a sculpture is useful to monitor the deterioration and to plan projects of restoration. The digitised model can also guarantee a "remote enjoying" of cultural heritage for didactic and spreading purpose, facing the distance from museums and cities of art. Moreover the integration with Rapid Manufacturing technologies allows the production of a copy of the sculpture, directly from the digital model, in short times.
A comparison, based on certain criteria of judgement, devices might be developed between two or more scanning in order to evaluate the most proper tool for the application taken into consideration (Boehler 2004; Broggiato; 2002; Iuliano; 1999).
In this work Reverse Engineering is applied to the digitisation of sculptural artworks of medium/small dimension. A scaled replica of Michelangelo's David was selected as case study. Since the free form surfaces of the small sculpture are quite complex, the use of an optical digitiser makes acquisition more rapid and less invasive in comparison to contact scanning. A triangulation laser and a structured light scanner are compared to select which device fits better for the job. The qualitative judgement of the two scanners is based on the authors' digitising experience, whereas the quantitative comparison is computed from the deviations between digitised data.
A copy of the digitised sculpture is produced by Rapid Prototyping for research, preservation and restoration purposes.

2. SCANNING DEVICES DESCRIPTION

2.1 Konica-Minolta Vivid-900

The first optical digitiser employed is Konica-Minolta Vi-900 (figure 1), based on laser triangulation. A stripe of coherent monochromatic light, coming from the device source aperture, is projected and swept across the working volume by means of a galvano mirror. The laser light is deformed by the surface of the scanned object. At the same time each scan line is captured in a single frame image by a CCD camera lodged in the device superior aperture (figure 2). Captured image frames are then elaborated according to the optical triangulation principle. The CCD camera also captures a 24-bit colour image containing information related to the object texture. The device is equipped with three exchangeable lenses (telephoto, medium and wide angle) to adjust the camera field to the object size.

Figure 1. Scanner Vivid-900 and rotary table

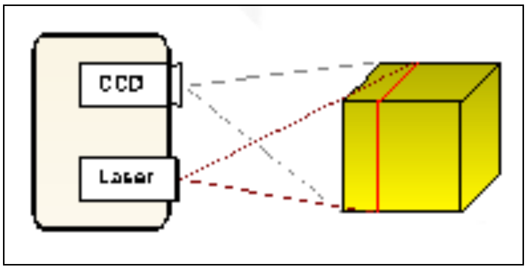

Figure 2. Vi-900's working principle

The software provided with Vi-900 gives more than a simple point cloud as output: the polygonal mesh, generated between points automatically, takes into account all connectivity information and it eliminates geometrical ambiguities.
A synchronized rotary table can be connected to the scanner to easily digitise complex three-dimensional objects on 360 degrees, rotating them by a user-definable angular step. Using the turntable, the software automatically computes the transformation required to register multiple scans all together.

2.2 GOM ATOS Standard

The other digitiser evaluated is the structured light scanner ATOS Standard (figure 3) produced in Germany by GOM GmbH. It exploits binocular vision as it has two Sony XC75 built-in CCD cameras which store images of the light fringes projected on the scanned object. The projector, placed in the centre of the sensor, projects a sequence of slides: four interference patterns (phase-shift technique) followed by six Gray coded binary images (figure 4). The 6-bit code allows distinguishing between $2^6 = 64$ columns in the field of view.

Figure 3. Scanner ATOS Standard

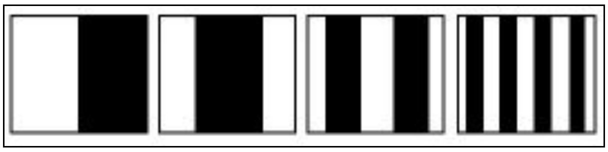

Figure 4. Gray code slide sequence

By means of a proper sensor calibration, binary codes are transformed into 3D positional data. The relation between interference fringes' phases and positions can be computed, but there's an ambiguity because phase repeats every 2π. The combination of the coarse Gray code technique with the finest phase-shift analysis helps to solve such ambiguity.
Two sets of exchangeable lenses are provided for the CCD cameras and the central projector. Lenses have to be changed in order to modify the scan area. Reference points are applied on the sculpture sticking adhesive targets (i.e. markers) in areas that contain less details (figure 5b). Multiple scans are automatically registered in one point cloud, as the scanning software recognises the fixed reference grid created by markers. There is a lack of data in the areas covered by markers, but GOM's software allows to complete the virtual model of the object closing such holes.

2.3 Comparison of the two scanners

Technical specifications of the two scanning devices, available on the datasheets, are shown in table 2.
From a qualitative point of view, the comparison, between the two digitisers, has been carried out according to six judgement criteria, which resume their characteristics (table 1):

- *Accuracy*: takes into account device performances in terms of accuracy and resolution;
- *Scanning Speed*: synthesises scanning rate, calibration and set-up times;
- *Robustness*: considers the device sensitivity to external disturbs such as a variation in light conditions or vibrations;
- *Ease of use*: denotes if specialized user is required;
- *Transportability*: takes into consideration the scanner easiness of transport and assembly plus the ratio of device dimensions to the maximum scan area.
- *Cost / performance ratio*: represents an estimate of the device cost related to its performances.

Characteristics	**Vi-900**	**ATOS Standard**
Accuracy	+	+ + +
Scanning speed	+ + +	+ +
Robustness	+	+ +
Ease of use	+ + +	+ +
Transportability	+ + +	+ +
Cost/performance ratio	+ + +	+ +

Table 1. Qualitative comparison of the two digitisers

(Legend: + Adequate + + Good + + + Very Good)

Specifications	**ATOS Standard**	**Vivid-900**
Sensor dimensions	610 mm x 160 mm x 125 mm	210 mm x 110 mm x 426 mm
Sensor weight	2.5 Kg	11 Kg
Scanning technique	Structured Light	Triangulation Laser
Scanning volume or area	100 mm x 80 mm x 80 mm to 350 mm x 280 mm x 280 mm	111 mm x 84 mm, 710 mm x 533 mm, 1300 mm x 1100 mm
Working distance	300 mm to 1100 mm	600 mm to 1200 mm
CCD camera resolution	768 x 572 pixel / 8 bit	640 x 480 pixel / 24 bit
Scanning time (per single view)	8 s	2.5 s
Accuracy	0.06 mm to 0.50 mm	0.17 mm on XY, 0.05 mm along Z
Multiple scans registration	Automatic (by marker network)	Automatic (only using rotary table)

Table 2. Technical specifications of the two digitisers

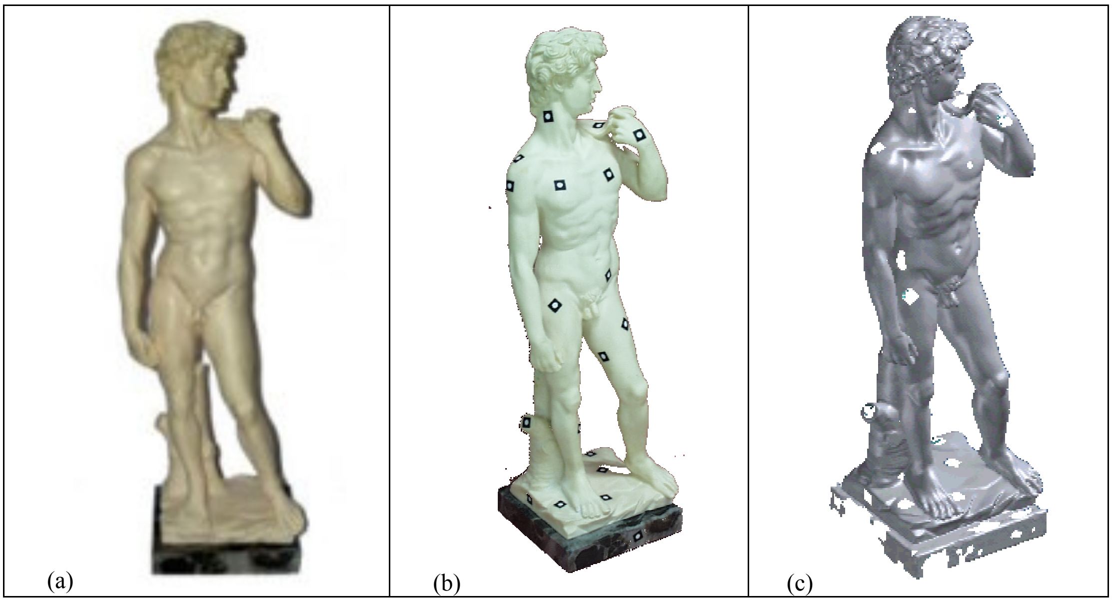

Figure 5. Michelangelo's David: Small Sculpture (a), makers' network (b), markers' holes (c)

3. THE SELECTED CASE STUDY

The sculpture selected as case study is a scaled replica of Michelangelo's David (figure 5a). The small statue is 300 mm high and its base measures about 100 mm x 80 mm. Before proceeding to digitisation, the sculpture surfaces have been accurately cleaned. It was not necessary to spray the sculpture with white powder, making it opaque in order to avoid light reflection. Possible dark stains of dust or other agents, deposited with time, would create zones with an absence of scan data, i.e. holes, on the surface of the three-dimensional model. Optical 3D scanners work correctly while digitising clear and opaque surfaces, but they have problems when objects are very shiny or too dark. A glossy object reflects the light and the acquired scan data might be noisy. A very dark surface, black at worst, totally absorbs the light and no data is acquired.

3.1 Vi-900 scanning

Twenty-nine scans have been necessary to digitise the whole sculpture. The telephoto lens was applied to Vivid 900 to assure the maximum accuracy and detail. Using such scanner configuration, the scan area did not include the artwork completely. For this reason, the three-dimensional model of the David has been reconstructed in two different phases. The upper half of the sculpture was digitised first, while the inferior part of the body was scanned in the latter phase.
At the beginning the artwork has been digitised including as many surfaces as possible in the scan field. The sculpture was set on the turntable in vertical position and the superior part was digitised with rotation increments of 45 degrees. Vi-900 was positioned about 1 m far from the object with an inclination of about 30 degrees with respect to the horizontal plane of the rotary table.
At first sight the most evident data lacks were collected on surfaces to which the laser light was incident along the tangential direction, e.g. some areas on the upper part of the shoulders and on the head. The sculpture was then positioned horizontally and new scans of the aforementioned zones were registered manually. At this point, no more macroscopic defects were noticed on the three-dimensional model, but small imperfections, as lacks or anomalies, were found in the polygon mesh through a careful analysis.

Since the geometry of the sculpture is quite complex, it is hard to make the laser stripe reach certain areas. For instance some zones under the armpits or next to the left hand are occluded by other surfaces of the artwork. Whatever way the David was placed, it was possible to digitise a small portion of those areas only, but not enough to overlap other data proceeding to registration. Such holes were closed creating polygons by selecting manually, one by one, closed figure vertices.
The inferior part of the sculpture was digitised following the procedure just explained for the superior half. The aforesaid problems of light occlusion were faced in this phase again.
The next step was the merging the two halves of the David's three-dimensional model. It was noticed that the inferior one was affected by a higher superficial noise than the bust (figure 6).

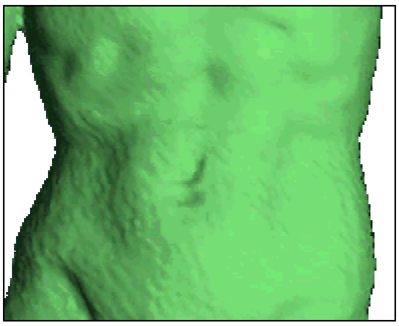

Figure 6. Vi-900 model after merging without smoothing

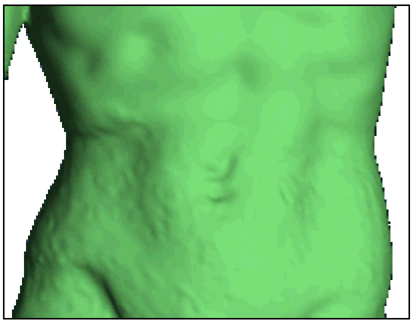

Figure 7. Vi-900 model after merging and smoothing

Such imperfection was ascribed to more than one reason, but the illumination of the environment was surely accountable: the inferior half of the sculpture was digitised toward the evening, when the external light was decreasing although the artificial light of the laboratory remained constant.
A smoothing operation was applied to the virtual model to make the mesh more homogeneous and to reduce the superficial noise (figure 7). Smoothing has involved a little loss of detail, more evident in areas rich of particulars, e.g. the head.

3.2 ATOS Standard scanning

Having considered the sculpture dimensions, the calibration of ATOS Standard was executed at a working distance of 750 mm, employing the set of exchangeable lenses for a scan area of 200 mm x 160 mm. Such configuration allowed to completely shot the artwork within the cameras field of view. Hence scanning separately the two halves of the sculpture was not necessary. Nevertheless about fifty scans were needed to digitise the David completely.
Problems of light occlusion were experienced again, just as in Vi-900's scanning. About half of the multiple scans were needed to reduce the extension of data lacks' areas. The scanning principle of stereoscopy guarantees a good accuracy, but on the other hand it is a limitation: the device is able to acquire three-dimensional data only on surfaces that are contemporarily visible from the light projector and both CCD cameras. Whatever way the artwork was positioned, for instance, David's left hand, grasping the sling near the shoulder, hides a part of the chin to one of the cameras. Moreover the software was not able to automatically close all the holes corresponding to markers (figure 5c): since targets were stuck on low curvature surfaces, they were not deformed too much, but their dimension (diameter of 3 mm) might have been excessive if compared to that of the sculpture.
The problem of markers holes in the virtual model could probably be dodged using smaller targets. However data lacks' zones were closed by creating NURBS surfaces, exploiting the proper software function.

4. COMPARISON BETWEEN SCANNED DATA

The times needed to digitise David's scaled replica with the two evaluated optical scanners are shown in table 3. The acquisition time includes the device calibration. The total time takes into account manual operations of point cloud processing (registration, merging, holes filling, etc.) to achieve the complete three-dimensional model.
Three virtual models were available for the comparison: the one achieved by means of ATOS Standard and two models reconstructed from Vi-900's scan data. The two Vi-900's models differ in the smoothing operation, which was applied only to one of them to reduce the superficial noise. RapidForm2004 software was employed to compare the virtual models. The three-dimensional model generated by ATOS Standard was set as reference for the comparison, since the nominal digitising accuracy of that scanner is higher.
The software by Inus Technology shows coloured maps of deviation as result of the comparison. Most of the inferior half of the sculpture is affected by error (figure 8). That is the evidence of the aforementioned superficial noise due to different light conditions during Vi-900's scans.

	ATOS Standard	Vi-900
Number of multiple scans	49	29
Time per single scan	8 s	2.5 s
Scanning time + repositioning	4 hours	3 hours
Total time	8 hours	13 hours

Table 3. Comparison between scan times

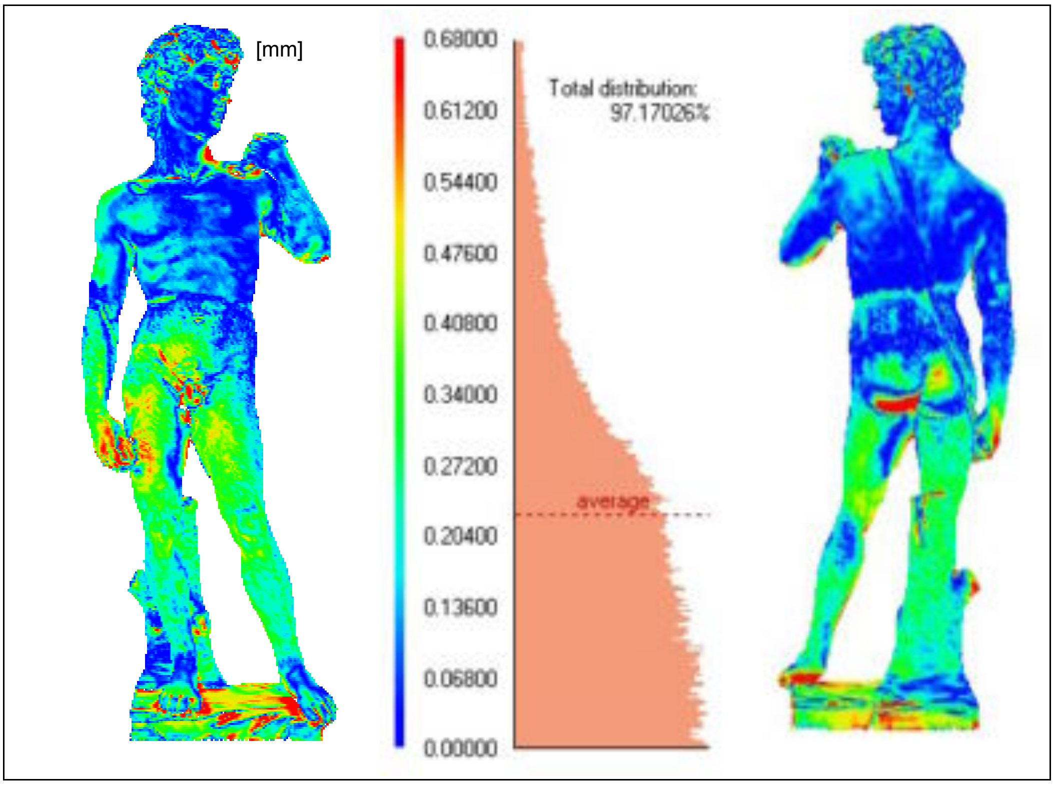

Figure 8. Deviation map of the front (left) and the back (right)

Models compared	Maximum Error [mm]	Mean Error (ε) [mm]	Standard Deviation (σ) [mm]
Vi-900 without smoothing vs. ATOS Standard	1.08	0.21	0.20
Vi-900 with smoothing vs. ATOS Standard	1.33	0.22	0.22
Vi-900 with smoothing vs. Vi-900 without smoothing	0.13	0.03	0.03
Vi-900 with smoothing vs. ATOS Standard (upper half only)	1.22	0.17	0.19
Vi-900 with smoothing vs. ATOS Standard (lower half only)	1.33	0.28	0.22

Table 4. Deviations measured between the reconstructed virtual models

The results of the comparisons between the different three-dimensional models are shown in table 4. The operation of smoothing, applied to improve the quality of the model scanned by Vi-900, has not increased the error very much. The average entity of the modification introduced by smoothing, in fact, was 0.03 mm.
If Vi-900's scans of the inferior half of the artwork have been repeated to reduce the superficial noise, the deviation would have decreased very little: the comparison, limited to the superior half of the model with smoothing, has point up a middle error of 0.17 mm, against 0.22 mm of the whole sculpture.
In similar applications, the value of the maximum deviation is not very meaningful, since it is referred to a single point or to a very small area. The distribution of the errors becomes thinner as the deviation value grows: the 97% of the points has an error lower than 0.68 mm (figure 8).

5. REPLICAS MANUFACTURING

By means of Rapid Manufacturing, three replicas of the sculpture were manufactured starting from the three reconstructed models exported in .STL file format (figure 9). The copies, produced by the 3D Printing technology using the Z-Corporation's Z402 printer, are made of plaster-based material for research and preservation purposes. The construction time of each prototype was 6 hours and 16 minutes using a layer thickness of 0.076 mm.

6. CONCLUSIONS

In this work, Reverse Engineering was applied to digitise sculptural artworks of small dimension. The two optical digitisers Vi-900 and ATOS Standard were compared using a scaled replica of Michelangelo's David as case study.
As result of the qualitative and dimensional analysis, taking into account acquisition times as well, we can affirm that both scanning devices fit for applications in the artistic sector.
The tolerances and the precision of 3D Printing technology, employed to manufacture the copies of the sculpture, did not allow reproducing the higher level of detail of the model digitised by the structured light device (figures 9 and 10).
A low cost integrated system to produce scaled replicas of sculpture can be obtained by using the triangulation laser scanner together with 3D Printing technology. If higher accuracy of the copies is required, the employment of the structured light digitiser is preferable, but it involves greater investment costs though.

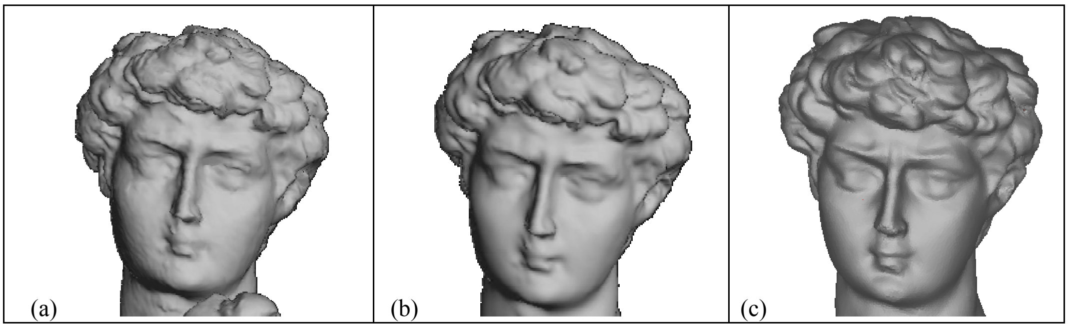

Figure 9. Virtual models: Vi-900 without smoothing (a), Vi-900 with smoothing (b), ATOS Standard (c)

Figure 10. Physical parts: original artwork (a), Vi-900 with smoothing (b), ATOS Standard (c)

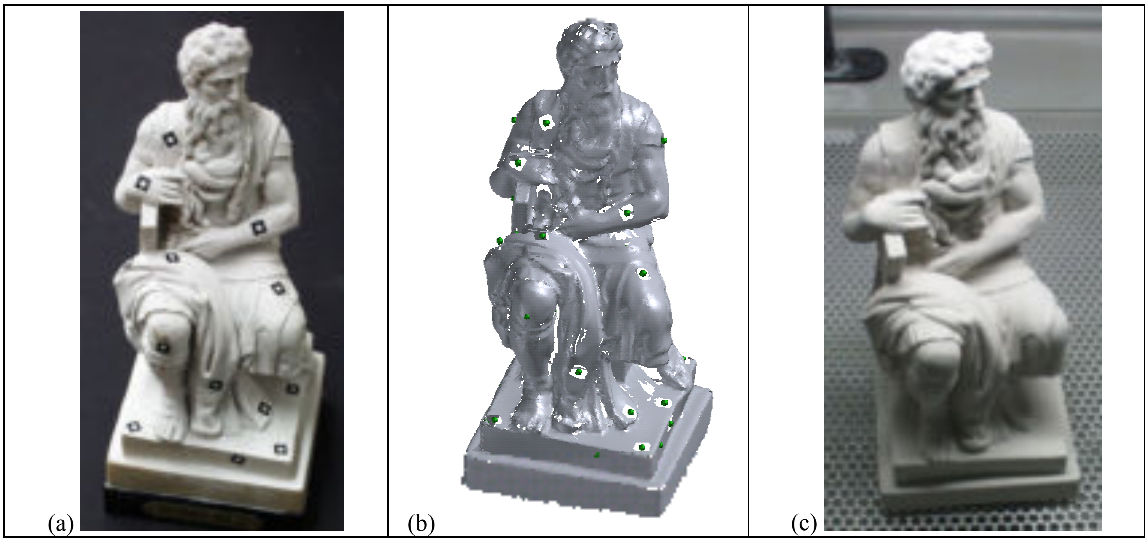

Figure 11. Michelangelo's Moses: sculpture with markers (a), 3D model (b), rapid prototyping replica (c)

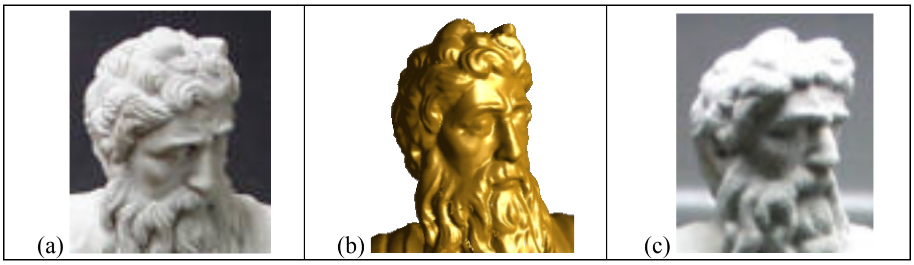

Figure 12. Detail of Moses' head: original sculpture (a), 3D model (b), rapid prototyping replica (c)

Moreover a more precise Rapid Prototyping technology, i.e. stereolithography (SLA), is worth using to better reproduce the details of the three-dimensional model.

Since ATOS Standard allowed to achieve the best result on David's virtual model, it was then employed to digitise another Michelangelo's masterpiece: the Moses. The scaled replica of the sculpture is 225 mm high and its base measures 100 mm x 140 mm. About half an hour was spent to prepare the sculpture for the acquisition. A thin layer of white powder was sprayed on the artwork to enhance the contrast and avoid undesired light reflections. Reference targets were stuck as well (figure 11a).

The surfaces of the Moses are slightly more complex than David's ones and about fifty scans were required to digitise the sculpture. Due to the higher number of light occlusions present in the artwork's shape, the three-dimensional model achieved by scanning contained a lot of data lacks (figure 11b). If compared to the David, more time was needed to close such holes by means of ATOS software and RapidForm2004.

A copy of the sculpture was manufactured by 3D Printing technology. Prototyping took 6 hours and 53 minutes with a layer thickness of 0.076 mm. Differences between the original sculpture and the replica can be appreciated looking at figure 12, wherein a detail of Moses' head is shown.

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