

Additive manufacturing of marble statues: 3D replicas for the preservation of the originals

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Abstract – A project for realising replicas of a couple of marble statues starting from reality-based 3D models is being presented in this paper. It takes advantage of the SfM technique to produce reality-based models, and to FDM system to 3D print the replicas. The paper presents an overview of the potential of additive manufacturing systems in the field of cultural heritage conservation and describes all the phases of the project, up to the evaluation of the correspondence between the original and the copy.

I. INTRODUCTION

The primary purpose of the project here presented is the replica of a couple of marble statues, that have been removed from their original place in the Baptistry of San Giovanni in Corte, in Pistoia, Italy (see Fig. 1).

The Superintendence consulted the Laboratory of Geomatics for the environment and conservation of cultural heritage at the University of Florence, whose researchers have already had many experiences in digital reproduction and tested different rapid prototyping techniques [1] [2].



Fig. 1. The original marble statues: St. Johan the Baptist (on the left) and St. Jacopo (on the right)

While several works report test about rapid prototyping techniques for reproducing reduced scale statues and other kinds of artefacts or some relevant samples in real scale, as in [3], this project presents a complete workflow for the digitisation of the statues, and the 3D printing and post-processing of their real-scaled replicas that are going to substitute the originals on the Baptistry.

Someone claims that we are living in the age of the culture of the copy, due to the pervasive presence of digital data in our everyday lives. Focusing on artefacts of artistic and historical interest, new technologies allow to transform their “real version” in a digital copy through a digitisation process (e.g. by laser scanning or photogrammetry) and then to reproduce a solid copy with additive or subtractive manufacturing. Obviously, nobody would exchange the real object with its copy, since specific differences between them (hopefully) persist. The concept of copying itself has changed its significance over time, in parallel with the development of new copying techniques. The most relevant positive aspect of the wide availability of “copies” is that they help to spread the knowledge about the original: “the copy leads us to the real” states Rosmarie Beier-de Haan [4], considering a West (European) cultural approach.

II. 3D PRINTING USES IN CULTURAL HERITAGE PRESERVATION

A “replica” is a copy closely resembling the shape and appearance of the original object. 3D printing techniques allow producing objective replicas, unlike what happens with the reproduction by a craftsman, who inevitably introduces some subjective interpretation, even though ingenious tools have always been used to provide stonecutters and sculptors with accurate geometric reference. Moreover, a handcrafted copy is usually made by tools, methods and materials similar to those used in the production of the original object.

In Italy, the “*fabricerie*” and “*opere*”, are institutions that provide for the conservation of the main religious building, carrying out continuous maintenance

interventions. In many cases, when it is no longer possible to restore certain structural or decorative elements, they replace them with copies [5], as the Fabbrica del Duomo di Milano does [6], supported in the last years by a geomatic team for the reality-based 3D modelling [7].

Alongside these traditional ways of reproducing artistic elements, the spread of additive manufacturing systems has opened up new perspectives [8]. Numerous experiences have led to the creation of small-scale copies for mainly exhibitive and educational purposes; digital archives, such as those of the digital library Europeana [9], are available to support these projects, and many other models can be found on platforms such as Sketchfab [10]. This work refers instead to the specific challenges that arise from full-scale reproductions of artistic artefacts of such a size that they cannot generally be printed in a single piece. Hereinafter is a list of some application areas that can benefit from the real-scale copying by digital fabrication techniques.

- Integration of missing or broken areas of artefacts or architectural components, as described by Bigliardi et al. [11] for the integration of some missing parts in a cornice in the Ducal Palace in Mantua.
- Production of high accurate shell for reducing the risk of damage to heritage artefacts can during shipping; Fatuzzo et al. [12] produce sculpture and packaging prototypes by additive manufacturing for aesthetic, functional and assembly evaluations of the packaging; Asla et al. [13] 3D print a 3D-fitted containers for packaging heritage artefacts which fit tightly the artefact.
- Making of moulds for reproductions in other materials: the replica of the northern door of the Baptistry in Florence started from 3D printed copies of the original, on which the silicone was poured, then the wax reproduction was made, and after a chiselling work to add small details, the plaster mould was made on the wax, and lastly completed with the bronze casting. The reproduction of one of the ceramic putti of the Innocenti Hospital in Florence also followed a similar workflow: the model was initially milled from polystyrene and then the plaster moulds, and finally the ceramic replica was made. [14]
- New modes of interaction between the public and collections in exhibitions and museums, in particular supporting and enhancing the fruition of artworks by people with learning difficulties, children, visually impaired and blind people [15].
- Reintegration or reconstruction of a plausible appearance of lost or partially lost objects, as we did for a missing part of a female figure in the frieze of the Spedale del Ceppo in Pistoia [16] or as reported by Neumuller for the ceramic lion originally in the temple of the ancient city of Nuzi (today's Iraq) [15].
- Spreading knowledge within museums, archives and other institutes [17] [18].

- Improving public engagement and awareness about cultural heritage at risk, as the Institute for Digital Archaeology did in 2015 printing and assembling a copy of the arch of Temple of Bel in the ancient city of Palmyra, destroyed by ISIS [19].

III. THE STATUES

The original statues were placed on top of the pilasters that frame the facade of the Baptistry of Pistoia, and they were removed from there in the mid-80s to safeguard their integrity; both show evident signs of deterioration due to the action of atmospheric agents. At present they are stored, with others ornamental stones coming from the Baptistry and the Cathedral, in the rectory of San Zeno in Pistoia. The statues are both of marble and are less than one meter tall:

- St. Johan the Baptist represents the saint as in his classical iconography, with a beard and long hair, dressed in "camel hair". It is, of the two, the one in worse condition, missing the feet; a plaster base currently supports it.
- St. Jacopo, patron saint of the city, wears its cloak and holds up the *titulus*.

They were both sculpted within the end of the fourteenth century when works for building the baptistry and its marble covering finished.

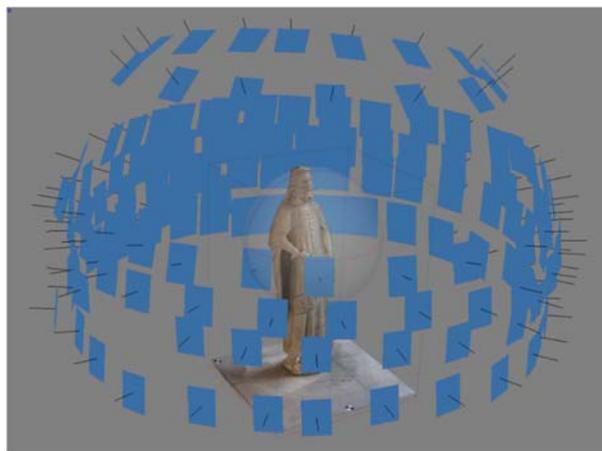


Fig. 2. SfM Project: camera network

IV. THE DIGITAL REPLICAS

High-resolution 3D models are required for supporting the replica process. They can be obtained by range-based techniques (active sensors) or image-based techniques (passive sensors). Stanco and Tanasi report the use of Nextengine laser scanner for the digital replica of a marble statue of the god Asclepius [20]. Skarlatos et al. tested on the same object optical and laser systems, discussing the pros and cons of both [21].

3D digital models were made in this project by SfM system (Fig. 2), allowing to fast and automatically reconstruct the surfaces, and offering, at the same time, an excellent overall accuracy.

A room with big windows only on one side was the place available for the survey. The statues, stored initially next to a wall, have been moved in the middle of the room. For acquiring the imagery, a camera D700 (by Nikon) has been used, with a 50mm lens; 800 ISO speed and aperture f/14 were set up. Considering the exposure time, generally longer than half a second, a tripod and a timed shooting were used.

To ensure a regular camera network, some references were marked on the ground, at a distance of about 1 m from the statues, for acquiring 16 photos spaced regularly all around the object, starting from a high of 20 cm from the ground and increasing the tripod high of 20 cm each turn. Additional photos were taken by hand, framing some statues details, in their most complex parts. 231 photos were taken on the St. Johan the Baptist statue, and 284 on the St. Jacopo statue. A check of the photo's quality was performed manually, and some colour and exposure enhancement were done while developing raw files.

Small black and white targets were placed on the ground (for St. Jacopo) or on the base of the statue (in the case of St. Johan the Baptist) and a couple of them were temporarily glued on the back of the statues in order to define a known distance almost vertical, out of the supporting plane. Mutual distances were measured by a tape meter, with an expected accuracy about 1mm.

The SfM projects were carried out in Photoscan software [22] (by Agisoft).

In the case of movable artefacts, as the statues are, there is no need to fix an external reference system, and referencing issues of the object can be disregarded, while is fundamental to scale the model correctly. For this purpose, redundant scale bars with reference distances have been introduced, and their residuals after the optimisation process are assumed as an indicator of the model accuracy. The RMSE of the scale bars is ± 1.5 mm in the St. Johan the Baptist project and lower than ± 1 mm in the Prophet project. The quality of the point-based models is good, with very few and small lack of data, and texture with good colour quality. Some slightly noisy data corresponds to the more shaded areas, due to the complex shape of some parts of the statues. The meshing process outputs models made by about 3.8 million triangles – St. Johan the Baptist – and about 2.5 million triangles – St. Jacopo. The digital models required some more processing steps before 3D printing: small holes were closed, and some topological issues were solved in the undercut parts, as at the bottom of the garment and behind the right arm of the St. Jacopo.

A strong decimation should entail a loss of details; at the same time, reduced numbers of polygons are required to manage the 3D model in the slicer software and to prepare it for printing. Therefore, different levels of decimation were tested before reaching the desired results, according to the maximum file size that was possible to process in the following step.



Fig. 3. A block at the end of 3D printing process: the inner hole and the space for the anchoring system are visible

V. THE 3D PRINTED REPLICAS

A variety of 3D printing systems are nowadays available, based on different technologies, such as deposition techniques, sintering strategies and other approaches; different kinds of materials can be used as well.

Considering the specific issues of this project (mainly, the need to print large volume objects, and to ensure an excellent open-air endurance), we choose a FDM (Fused Deposition Modelling) 3D printer, in which a resistance heat a filament made of plastic up to temperatures of 200-250°C and then passed through a nozzle which, guided by a mechanical arm, deposits the following layers to give shape to the object.

A 300h (by Kloner 3D) [23] 3D printer has been used to produce the replicas. It allows to print a volume of 320mm x 260mm x 330mm, that is a very large volume for this category of printers.

The print area on the horizontal plane is large enough to encompass all the horizontal sections of both statues, even if it was necessary to partition them in blocks about 20 cm high, as better described later.

Since the reproductions must be exposed to atmospheric agents, the most appropriate material for their printing has been carefully selected: a filament called ASA (Acrylonitrile Styrene Acrylate) has been chosen because it is produced to withstand considerable temperature ranges, ensure stability to sunlight and adequate mechanical qualities. Its version without added pigments was used, offering an ideal base for the subsequent processing steps.

Both models were edited capping the bases to obtain watertight surfaces, and a series of reduced scale prints of complete statues were made. Then some full-size elements were printed to evaluate possible work problems and final appearance.



Fig. 4. The replica of St. Johan the Baptist made up of several blocks, before their assembly



Fig. 5. One of the treatments tested for the finishing of the replicas: on the left the original model, on the right after a mild sandblasting and a colour tune.



Fig. 6. The replicas during the finishing operations made by the restorer

To limit the printing time to a maximum of 48 hours [24] (to contain the risk of print failure) both statues were segmented in blocks by horizontal cutting planes (Fig. 4). Each block has been individually imported into the 3D printer management software to compute the slicing and to evaluate the fundamental parameters of the printing, which are: height of the layer, thickness of the external surface (choice made in view of the post-print treatment) and of the internal filling structure.

Thick layers avoid delamination issues but increase the staircase effect: to balance the resistance needs with the appearance requirements, after some test, the layers height was set to 0.3mm.

The external surface play a structural role and it is at the same time the supporting material for post-printing finishing operation; it was set to 1.8mm.

The infill structure is defined as a percentage of the inner volume of the model: the denser the filling is and the more resistant the pattern is, but at the same time more material and longer printing time are needed. To balance all these aspects the infill was set as 10% of the volume.

The cutting plane position was designed considering both the printing time and the shape of the resulting blocks, avoiding printing supports, which are essential to work with overhanging parts, but obviously require extra material and finishing procedures for their removal. The sections to be managed with more attention have proved to be those in the area of forearms and elbows because they have the most pronounced overhangs and, in the case of the St. Jacopo even the largest undercuts.

During the restoration works, two steel plates were fixed on the crowning of the Baptistery where the replicas will be placed. Each of the statues have a corresponding steel flange to which a vertical tube has been welded; all the printed blocks have a hole for letting it cross all the model, support the replica and to fix it to the support. In the St. Johan the Baptist replica, the tube is vertical, while the posture of the St. Jacopo statue required to design the

support blending it towards the rear starting from the second block. In both cases small holes were left in the printed parts for insert some mechanical fixing (Fig. 3); since all the process was performed on the digital model, it was possible also to design “caps” with a shape perfectly fitting the holes, completely hiding the fixing system.

Expert restorers glued with special resin the blocks of every statue and plastered their junctions (Fig. 6); finally, they treated the external surface to obtain a homogeneous colour tone (Fig. 8).

VI. DISCUSSION

The accuracy evaluation of the digital model can be assessed thanks to the redundant distances (scale-bars) that are considered during the SfM computation; as reported in Section IV, the RMSE is about ± 1.5 mm.

No standardised procedures are established to define the accuracy of a 3D printer, and this is generally an indication that is missing from the datasheets. However, the printing settings condition the quality (also from a metric point of view) of the final result. Instead, the nozzle diameter (in planimetry) and the thickness of the layer (in elevation) can be used as reference values for the resolution.

The Kloner 300h 3D printer has a nozzle diameter of 0.5mm; for our project, the height of the layers was set to 0.3mm. As described before, some dimensional variations are expected in the printed blocks due to thermal effects. Moreover, the glueing of the blocks and, above all, the surface finishing phase, could have introduced further variations with respect to the shape of the digital model. In order to evaluate globally any deformations that may have occurred during the entire process of making the solid model, a photogrammetric survey of one of the replicas (St. Johan the Baptist) was achieved at the end of the project. The deviations respect to the survey of the original statue are illustrated in Fig. 7 and are limited to few millimetres.

The project allowed to assess the potential of reality-based 3D models and FDM printing systems on a considerable case study. When the project started, all the expert involved were not so sure about the results they will gain. All of us knew very well his field of study, but it was not the same for the others. The very idea of "best resolution" or "satisfying visual aspect" or "work done in quick time" is interpreted differently by experts in different disciplines and requires thoughtful and open dialogue to identify feasible, functional, efficient and effective solutions.

In conclusion, the ability to capture detailed three-dimensional data and to exploit additive manufacturing techniques opens up several options for restorers, interested in material preservation as well in preserving the concept of authenticity: digital copies and 3D printed objects inspire new thoughts about the ideas of image and matter preservation and integration, and originals substitution.

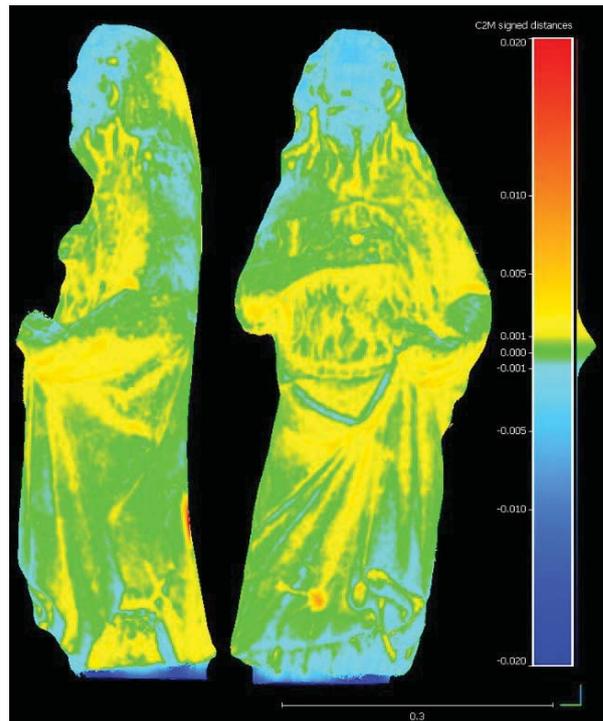


Fig. 7. Signed distances between the 3D model of the original statue and that of its replica



Fig. 8. The replica of the St. Jacopo, before the block assembly (on the left) and after the finishing operation made by the restorer (on the right)

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