The Construction of Multisensory Models of Ancient Statuary, between Innovation and Tradition

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Abstract

The research focuses on the development of a scientific methodology for the creation of copies of Cultural Heritage without scale reduction, capable of simulating the physical qualities of original materials such as marble, to allow for multi-sensory enjoyment. Using innovative technologies and traditional techniques, the process begins with a massive data survey, identifying a digital reference model. Subsequently, the construction of a 'new original' by 3D printing in PLA and deblocking paves the way for the creation of copies by casting with a cement mixture that can simulate the materiality of marble. The choice of materials, subjected to perceptual and thermal tests, plays a crucial role in the selection of the material to be used to replicate the characteristics of the original. The validation of the geometric results demonstrates the compatibility of the physical models with the research objective. Finally, the study introduces the concept of 'metric reliability level' as an essential parameter for the scientific validation of the results. The research, carried out with the collaboration of the Soprintendenza Speciale Archeologia, Belle Arti e Paesaggio of Rome and the Pontifical Commission for Sacred Archaeology, focuses on the copy of the Head of St. Elena in the Mausoleum of St. Elena in Rome, highlighting the applicability of the proposed methodology in the context of Cultural Heritage.

Keywords: 3D model, Structured Light Scanner, SfM, Head of St. Elena, 3D Printer models.

Introduction

Current 3D printing technologies have substantially modified the construction methods of analog models. Depending on the type of object and the scale of the physical model desired, it is possible to select the most suitable printing technology and support based on the required performance characteristics, offering users a considerable number of possibilities. The market for printing materials has focused particularly on identifying solutions, all based on plastic or resin, which vary substantially in the mechanical qualities of the finished product, but currently, there are no methods that allow for the simulation of the typical qualities of materials used in sculpture. This is not about simulating chromatic properties, which is possible in some cases, but rather about being able to create objects capable of simulating physical qualities, such as temperature and texture of the original material, which would find an interesting application for the multisensory enhancement of many Cultural Heritage assets, especially for the reproduction of ancient statuary.
This contribution focuses on the results of research aimed at defining a methodological and technological solution capable of overcoming this limitation by allowing the creation of copies of Cultural Heritage assets without scaling down and capable of simulating the qualities of the original marble materials. The copies thus produced, precisely because they can reproduce all the characteristics of the original, can find immediate use in

the enhancement field, allowing for a multisensory enjoyment of the assets while ensuring the preservation of the originals [1].
Tradition and innovation meet in this experience that, starting from reality, allows for a return to reality through the creation of a "new original" built with a 3D printer, with which to create a contact matrix to be used as a mold for the construction of a copy through casting, capable of reproducing the material properties of the original object.
Through a structured process that integrates innovative technologies and traditional techniques, the research focused on the entire process of creating the copy, scientifically validating all work phases: from the acquisition of surfaces to the identification of procedures for the realization of copies, to the evaluation of the specific characteristics of the material with which the originals are made to ensure that they are reproduced in the copy, to the identification of procedures for the control and scientific validation of all work phases.
The research, conducted with the contribution of the Soprintendenza Speciale Archeologia, Belle Arti e Paesaggio of Rome and the Pontifical Commission for Sacred Archaeology, describes the activities necessary for the construction of a copy of an archaeological find at a 1:1 scale to allow for broader multisensory enjoyment within the museum path of the Mausoleum of Saint Elena in Rome.

Fig. 1. Head of Saint Elena, IV century, Mausoleo di Saint Elena, Rome (photo by the author).

The case study

The object of the case study is the so-called *Head of Saint Elena* [Inv. PCAS-82] (fig. 1), preserved at the Antiquarium of the Mausoleum of St. Elena, a cultural site of the Special Superintendence for Archaeology, Fine Arts and Landscape of Rome reopened in 2019 after extensive restoration thanks to the Pontifical Commission for Sacred Archaeology, which currently manages part of the exhibition that includes the nearby catacombs of Saints Marcellinus and Peter [Giuliani 2015; Bochicchio 2019].
The Mausoleum of St. Elena is one of the most important architectural complexes of paleo-Christian Rome from the 4th century. Built between 315 and 326, originally intended to serve as a burial place for Emperor Constantine himself, it was later used as a tomb for Flavia Julia Elena, the emperor's mother, who died in 329.
The study aims to physically reconstruct the Head of St. Elena, a marble artifact from Mount Pentelicus that is in good condition. The head consists of a fragment of a face measuring 215 × 213 × 218 mm characterized by a "turban" hairstyle with a large braid wrapping around the hair, divided by a central parting, and folded into regular waves that descend to the nape, hiding the ears.
The study of the artifact, authorized by the Pontifical Commission, is part of a promotional effort initiated in 2021 by the Special Superintendence of Rome for the completion of the Antiquarium of the complex [Giuliani 2016].

The survey

The survey constitutes an essential step for the construction of the database necessary for obtaining a copy, whether it be digital or physical. Much has been written in recent years about the possibilities offered by various mass acquisition technologies applied to statuary objects, with the development of dedicated workflows that exploit Lidar techniques and SfM methodologies. Among the various contributions in the literature, it is useful to mention some studies dating back more than 20 years ago [Levoy et al. 2000; Bernardini et al. 2002; Fontana et al. 2002; Guidi et al. 2004] that allowed for the first time testing the potential of range-based acquisition tools, defining the pipeline [Bernardini, Rushmeier 2002; Godin et al. 2002] and paving the way for their extensive application in the Cultural Heritage domain.
The reasons that have seen attention focused on statue complexes can be traced back to the geometric and formal nature that characterizes statuary surfaces, which are of considerable complexity. Given the sensitive nature of the objects under study, the use of contact surveying tools is not applicable, and this fact has led to the development of techniques suitable for collecting a considerable amount of data necessary for understanding the surfaces themselves. Experimentation began around 2000 with photogrammetric techniques, which, although not yet able to extract a significant number of homologous points in space from pairs of photographs, already highlighted the potential of these methodologies for the construction, albeit simplified, of free-form surfaces [Grün et al., 2002]. Certainly, some early discussions on the potential use of images for building 3D models [Curless 2000] led in the first five years of the 2000s to the definitive development of Visual Structure from Motion techniques [Szeliski, Kang 1993] capable of reconstructing complex 3D artifacts, sparking discussions on the use of active or passive systems for small artifacts [Remondino et al. 2005] and leading image-matching techniques to be an effective alternative to range-based systems [Remondino et al. 2014]. These experiments have allowed the implementation of a now established surveying process applied in multiple fields of Cultural Heritage. These boundary conditions define a complex research framework that motivates the numerous experiments in the field of statuary.
In this context, the research fits in, building on the information obtained from some previous experiences [Russo et al. 2022], aiming to define scientific parameters for the construction of the database and for result validation. Considering the objective, namely reproduction without scale reduction, attention has been focused on identifying control parameters and threshold values capable of ensuring the best metric reliability for all models. The parameters considered were point accuracy (with a threshold value of 0.1 mm) and point cloud resolution (with a threshold value of 0.2 × 0.2 mm). These values have been shown to be achievable both in the acquisition and printing phases [2] (fig. 2).
For the acquisition carried out within the Antiquarium (fig. 3), two different survey methods were tested: using SfM technique and Structured Light Acanners [3].

The SfM methodologhy

The Structure from Motion (SfM) methodology represents an effective solution both in terms of time and logistics. The ability to take a considerable number of shots allows for the construction of high-detail models, namely point clouds with resolutions even lower than a tenth of a millimeter, and therefore compatible with threshold values.
The use of this methodology has allowed the attainment of a point cloud model quantitatively compliant with the project's threshold values. For scaling the point cloud, a cloud-to-cloud comparison was performed with a

Fig. 2. Results of the acquisition phase: on the left, textured point cloud model obtained with SfM; on the right, textured point cloud model obtained with structured light laser (graphic elaboration by the author).

model whose reliability is compatible with the project parameters. Since it's not possible to interact with the original artifact using contact instrumentation with accuracies lower than a tenth of a millimeter, it was decided to use the model created with structured light scanning as a reference, with instrumental reliability declared at 0.1 mm and a resolution of 0.2 × 0.2 mm. The construction of the interpolation mesh surface of the point cloud highlighted the limitation of this methodology, particularly due to the presence of a large amount of noise, especially in areas where the original surface was smooth.

The structured light scanner

A second scanning activity was carried out with a handheld structured light scanner [4], considering the variable acquisition distance, which can be estimated at 0.2 mm and capable of producing a point cloud with a mesh of 0.2 × 0.2 mm. The use of this tool allowed for the construction of a reliable and metrically reliable model with accuracy consistent with the study's requirements. The analysis of the resulting point cloud from the acquisition highlighted an almost total absence of noise, with positive effects for the subsequent mesh surface processing. The best results were evident in the definition of smooth surfaces that the instrument can recognize and discretize with a very low level of noise. Precisely due to its geometric characteristics, the models created from the database obtained with this instrument –both point clouds and meshes– were considered "Gold Standard" in all validation activities of the various phases of the research. Due to the better quality of the mesh surface, the model generated from the data acquired by the structured light scanning was used in the 3D printing phase for the creation of the "new original".

Fig. 3. The acquisition phase carried out after setting up a set at the Antiquarium of the Mausoleum of Saint Elena (photo by the author).

The construction of the copy: from the real to the real through the digital

Once the digital mesh model of the original object was created, it was possible to construct the physical model with 3D printing. Among additive manufacturing technologies, filament printing was preferred using a Delta Wasp 4070 loaded with white polylactic acid (PLA), extruded with a 0.4 mm nozzle, and set to produce slices of 0.2 mm. The *Fused Deposition Modeling* (FDM) technology was chosen particularly because currently this solution is the only technology capable of reproducing objects of considerable size and therefore potentially the only one usable for the construction of copies of large statues (fig. 4).
Once the PLA copy was built, it was subjected to sanding (fig. 5) with a mixture based on calcium carbonate and resin applied with a brush to eliminate the ridges typical of the slicing process. The result of this operation allowed the definition of a new original with which traditional techniques for constructing copies by contact could be applied. Specifically, a mold was created using silicone rubber capable of adhering perfectly to the surface of the new original to produce a negative to be used for the elaboration of the final copy (fig. 6).
Once the silicone rubber was made and the mold reassembled (fig. 7), the physical copy was then made by pouring a cement-based mixture selected according to the desired material effect to simulate the material of

the original.

The materials for the construction of the copy

The choice of materials to be used in the casting operation inside the silicone mold was a substantial part of the research due to its key role in the perceptual characterization of the copy [Senatore et al., 2022]. Among the characteristics capable of qualifying a surface, texture to the touch, resistance to abrasion, hardness, permeability to liquids and fats, and heat dispersion capacity were evaluated. For the assessment of the specific qualities of the possible solutions for the mixture to be used in reproduction, samples were constructed with two different binders, one cement-based and one resin-based, to which marble powder was added in various percentages. The samples were subjected to tests to qualify them in relation to the parameters previously defined.
At the same time, the same control tests were carried out on some original pieces made of clay or marble material to create references for comparison (fig. 8).
The verification revealed some common properties among the samples in relation to the binder used:

- mixtures with a high resin content were characterized by excellent resistance to external agents, good wear resistance, good elasticity, and excellent insulating capacity, meaning they could retain heat for a long time. Perceptually/tactilely, the samples showed almost no texture. Further investigation regarding heat dispersion capacity revealed that, under similar environmental conditions, resin-based materials took up to 5 times longer to disperse a certain amount of heat compared to stone, leading to the perceived sensation of warmth when in contact with plastic surfaces;
- cement-based mixtures showed lower resistance to external agents with wear-related issues, partial permeability to liquids and fats, greater rigidity, and good heat dispersion capacity. Perceptually/tactilely, the samples exhibited a texture stone-like. A specific study of the thermal capabilities of the materials identified some mixtures with heat dispersion similar to that of stone and marble;
- for cement-based mixtures, it is possible to improve resistance to external agents by applying a resin-based film at the end of the drying process, thereby modifying heat dispersion capabilities.

Once the comparison values were determined by measuring the same parameters on the original objects, it was possible to compile a list of solutions classified according to their ability to reproduce the characteristics of the originals. These solutions could be used as needed for the different materials for which a physical copy was required (fig. 9).
Considering the haptic use of the new copy, i.e., the copy's ability to tactually convey the sense of the original material to the user, the choice of material for casting fell on a mixture (sample 5) based on cement and marble powder with properties that closely resemble those of the original marble.

The validation of the geometric results

All models obtained, both digital and physical, underwent metrological verification by comparison with the reference digital model identified in the structured light

Fig. 4. 3D printing: on the left, the printing process; on the right, detail of the surface: the typical steps of the production process are evident (photo by the author).

Fig. 5. Blending: on the left, the new original obtained with blending; on the right, detail showing the elimination of the steps from the printing process (photo by the author).

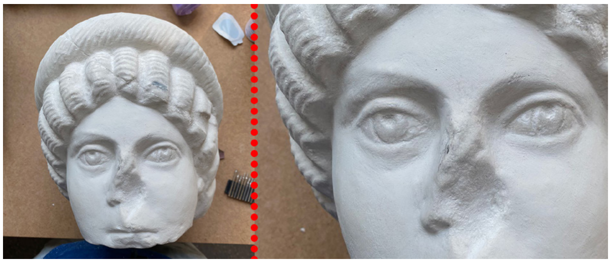


Fig. 6. Construction of silicone molds starting from the new original (photo by the author).

Fig. 7. The reconstructed mold ready to receive the cement and marble powder mixture for the construction of the copy (photo by the author).

scanning of the original object (Gold Standard). For the physical models, a new survey was conducted using the structured light scanner. To verify the actual instrumental response to the case study, no smoothing or filtering algorithms were applied to the digital models used for comparison.
The different models were imported into the CloudCompare program, and after performing the rotation-translation operation without scaling, deviations between the individual models were analyzed. Each model was used at its native resolution, avoiding the introduction of decimation processes that could affect the model's shape and thus preserving the detail obtained during acquisition.
From the metrological comparison, several considerations emerged. Overall, the discrepancies between the different models were extremely small and not significant. Regarding the SfM methods, it emerged as an extremely reliable technique for geometric and radiometric detection, albeit with considerable levels of noise detectable, particularly for portions of extremely smooth surfaces. The application of a smoothing filter was discarded due to the variations in the nature of the surfaces that would have affected the result.
Regarding the comparison between the reference digital model and the physical models, both the one in PLA with subsequent sanding (matrix) and the one made for casting, it was noted that the various production steps introduced geometric variations that were quantitatively insignificant, except for specific abrupt changes in orientation or for the presence of significant depth variations. In general, the difference between the physical models and the Gold Standard was found to be compatible with the research objective, as evidenced particularly by the standard deviation data, which was found to be less than or equal to 1 mm for all models (fig. 10).

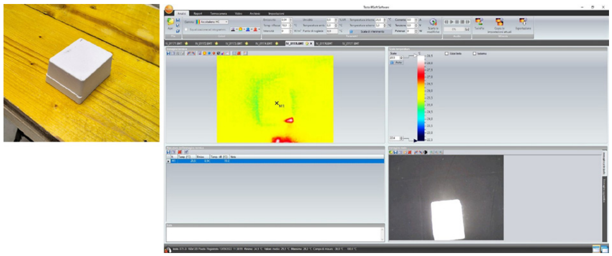
Conclusions

The study aimed to identify a scientific no-contact methodology for creating copies of Cultural Heritage artifacts without scale reduction, consistent with the originals both metrically and materially, aimed at multisensory fruition.
Current production methods still have a series of technological limitations that do not allow for the automated construction of this type of artifact, which could have enormous benefits for the conservation and valorization of Cultural Heritage items within collections and museum

deposits. To overcome this limitation, the study, integrating innovative technologies and traditional techniques, has demonstrated how the construction of copies capable of reproducing the form, texture, and material of the original is possible (fig. 11).
Simultaneously, the research sought to define some objective parameters based on which copies and models can be scientifically validated. This aspect, relevant when activating digitization processes, becomes a priority when it is necessary to construct an object at real scale. To this end, the study considered the level of metric reliability, a quantitative scientific datum that can be considered as the amount of information necessary to ensure the reliability of results, usable both in the construction and validation phases. In the past, the amount of information provided by a model was inherent in the concept of scale and represented an essential reference for evaluating the quality of a product. The ability to build digital models has introduced new complexities in defining the level of quality, requiring the determination of new parameters for controlling results –the level of metric reliability, a parameter closely linked to acquisition and production technologies– has proven to be a valid tool for validating processes and results.
The research has shown that operating in the field of digitization, only the construction of a system of parameters for the scientific evaluation of products will allow adequately considering the quality of models, and this attention is desirable to become a practice not only in the context of the study described here but, more generally, whenever a digital model is constructed, in order to qualify it and simultaneously to give value to the information that can be derived from it.
Regarding future developments, the study presented here has demonstrated the possibility of simulating objects made of earthenware and marble, and activities are already focusing on identifying a low-cost strategy capable of reproducing the texture and temperature of metallic objects, expanding the possibilities of constructing copies to all artifacts characterized by this type of material. In parallel, due to the close relationship between physical copies and the instruments used in the process of digitization and 3D printing, the study is focusing both on improving the accuracy levels of different models and on identifying technological solutions capable of automating the process of constructing the copy, minimizing human interaction to improve accessibility to the use of copies in the context of Cultural Heritage valorization.

Fig. 8. Test with thermocamera on samples for the evaluation of the return time to ambient temperature of the material following contact (photo and graphic elaboration by the author).

Fig. 9. Evaluation of the return time to ambient temperature of the mixture samples for comparison with the material of the original. The y-axis indicates the temperature in degrees Celsius, and the x-axis indicates the time in seconds (graphic elaboration by the author).



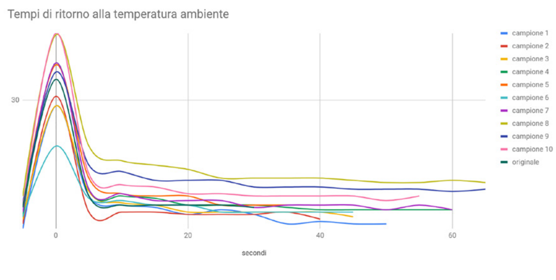
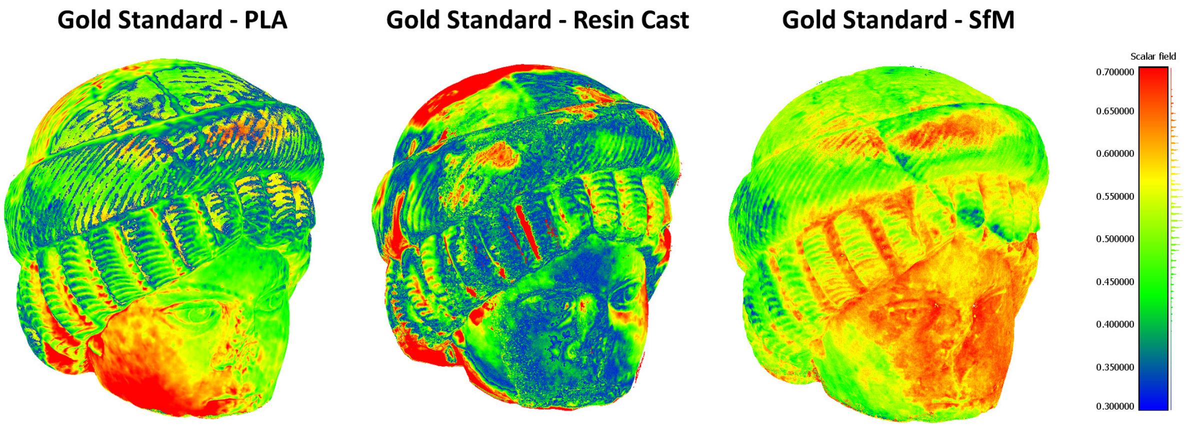


Fig. 10. Comparison and deviation in mm: Gold Standard - PLA physical copy; Gold Standard - Cast physical copy (graphic elaboration by the author).

Fig. 11. The new copy made by casting (photo by the author).



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Notes

[1] The proposal, using non-contact methodologies, complies with current legislation, particularly the limitation imposed by the Code of Cultural Heritage, Art. 107 paragr. 2 of Legislative Decree 42/2004, which prohibits the construction of copies of works subject to protection using traditional contact techniques.

[2] - The contribution constitutes the concluding summary of the results of a long research activity funded by the University of Rome Sapienza (Seed PNR 2022 and 23 Call for Proposals), with the undersigned as PI. Over time, some of the partial results achieved during the study phases, which are systematically and organically presented here, have already been published in national and international conferences. For specific insights, please refer to the bibliographic references present in the text and bibliography.

[3] Reference is made specifically to filament printers, which currently represent the only operationally feasible solution to produce large-scale copies. Although of significantly higher quality with the ability to create submillimeter layers, resin printers are still limited to objects no larger than 30x30x30 cm, incompatible with most Cultural Heritage artifacts. At the same time, filament printers allow the construction of objects, including considerable dimensions, which can reach, in some industrial versions, a size of 1x1x1 m.

[4] The choice of sensors did not include the use of terrestrial laser scanners due to the impossibility of obtaining point clouds with reliability compatible with the project's defined requirements.

[5] Scans were performed using the Skantech Ireal 2S capable of producing a point cloud with a resolution of 0.2x0.2 mm and point accuracy of 0.1 mm. The instrument is specifically designed for body scanning. This feature, along with the presence of dedicated optimization filters, proved to be a significant advantage in constructing an orderly and optimized point cloud, which was effective in building a mesh surface describing both smooth and rough surfaces.

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