ACTA IMEKO
ISSN: 2221-870X
September 2024, Volume 13, Number 3, 1 - 2

Journal contacts

ABOUT THE JOURNAL

Acta IMEKO is an e-journal reporting on the contributions on the state and progress of the science and technology of measurement. The articles are mainly based on presentations presented at IMEKO workshops, symposia and congresses. The journal is published by IMEKO, the International Measurement Confederation. The ISSN, the international identifier for serials, is 2221-870X.

ABOUT IMEKO

The International Measurement Confederation, IMEKO, is an international federation of actually 42 national member organisations individually concerned with the advancement of measurement technology. Its fundamental objectives are the promotion of international interchange of scientific and technical information in the field of measurement, and the enhancement of international co-operation among scientists and engineers from research and industry.

ADDRESSES

Principal Contact

Prof. Francesco Lamonaca
University of Calabria
Department of Computer Science, Modelling, Electronic and System Science
Via P. Bucci, 41C, VI floor, Arcavacata di Rende, 87036 (CS), Italy
E-mail: editorinchief.actaimeko@hunmeko.org

Support Contact

Dr. Dirk Röske
Physikalisch-Technische Bundesanstalt (PTB)
Bundesallee 100, 38116 Braunschweig, Germany
E-mail: dirk.roeske@ptb.de

ACTA IMEKO
ISSN: 2221-870X
September 2024, Volume 13, Number 3, 1 - 5

Sculptures for a tactile fruition: The head of Sant'Elena

Michele Russo[1], Luca J. Senatore[1], Raffaella Giuliani[2], Rocco Bochicchio[3]

[1] *Department of History, Representation and Restauration of Architecture, Sapienza University of Rome, Rome, Italy*
[2] *Pontifical Commission for Sacred Archaeology, Vatican City*
[3] *Special Superintendency of Archaeology, Fine Arts and Landscape of Rome, Rome, Italy*

ABSTRACT
The creation of physical replicas of statues is not a novel concept; however, it continues to present various aspects worthy of investigation. On one hand, there is the need to optimize digital models for their physical experience while retaining distinctive features. On the other hand, there is the development of a robust pipeline for constructing reliable physical copies concerning morphometrics and materials. Both stages necessitate experimentation and comparisons, allowing for the validation of processes to achieve scientifically accurate results. This article, using the case study of the head of Sant'Elena preserved within the mausoleum of the same name, suggests comparing different processes of physical and digital 3D acquisition and reproduction of the artwork. The goal is to enhance its accessibility for individuals with visual impairments.

Section: RESEARCH PAPER

Keywords: structure from motion; structured light laser scanner; sculpture twins; mausoleo di Sant'Elena; phygital asset

Citation: M. Russo, L. J. Senatore, R. Giuliani, R. Bochicchio, Sculptures for a tactile fruition: The head of Sant'Elena, Acta IMEKO, vol. 13 (2024) no. 3, pp. 1-5. DOI: 10.21014/actaimeko.v13i3.1816

Section Editor: Fabio Leccese, Università Degli Studi Roma Tre, Rome, Italy

Received February 28, 2024; **In final form** May 6, 2024; **Published** September 2024

Corresponding author: Luca J. Senatore, e-mail: luca.senatore@uniroma1.it

1. INTRODUCTION

The current contribution primarily resides within the digitization domain, focusing on the knowledge, preservation, and dissemination of Cultural Heritage. The research outlined in this context pertains to the examination of the "Head of Sant'Elena," with the objective of proposing the development of a 1:1 scale replica designed for tactile utilization. The intention is to enhance the appreciation of the artwork by facilitating communication through a tactile pathway, catering to individuals with visual impairments or blindness. The object, belonging to the Pontifical Commission for Sacred Archaeology, originates from the Mausoleum of Sant'Elena, a site overseen by the Special Superintendence of Rome and the Pontifical Commission.

The research process commenced with 3D digitization, employing a structured light 3D scanner. This approach provided a fresh perspective on the artwork, unveiling various potential scenarios. The resulting digital twin has enabled the creation of products serving diverse purposes aligned with specific characteristics. The primary objective is to produce a 1:1 scale physical copy of the model. Each step in the production and digital transformation process will undergo metrological testing, assessing the accuracy of the digital model and the reliability of the production process.

The field of 3D digital surveying of statuary complexes has been a subject of research for over two decades, marked by pivotal experiments in active and passive non-contact surveying techniques for Cultural Heritage [1], [2]. These experiments laid the groundwork for the development of a 3D acquisition pipeline, setting the stage for widespread applications in the Cultural Heritage domain [3].

The initial emphasis on statuary complexes in the early 2000s can be attributed to the formal complexity these statues present in space, posing challenges for surveying. During this period, range-based tools were compared with early applications of building 3D models through images [4]. The subsequent development of Visual Structure from Motion techniques enabled comparisons between active and passive systems for minor artifacts [5]. These experiments refined an acquisition process that is now well-established across different scales in various Cultural Heritage applications.

A significant factor contributing to the focus on statuary complexes lies in the favorable survey conditions offered by their smaller size. The reduced scale of statues allows for better exploitation of high-resolution range maps, leading to developments in the multi-resolution domain, even extending to larger scales such as urban models [6].

Statues also present a dual challenge concerning material and surface finish, which can impact the acquisition conditions for optical instruments. Active instruments may face challenges with optically non-cooperative materials or back-scattering problems [7], while passive instruments are constrained by external light conditions, material conservation factors, surface patinas, and light reflection levels [8].

These complex conditions define a comprehensive research framework, motivating numerous experiments in the field of sculpture. Over the past two decades, surveying techniques have evolved with advancements in instrumentation and digital data management, reducing hardware sizes by optimizing optical and digital aspects [9]. The interest in low-cost techniques for the 3D acquisition of minor archaeological and statuary artifacts [10]-[12] has led to the development of well-defined methodologies with increasingly accessible 3D systems. This has enabled massive 3D acquisition campaigns of entire museum collections, creating accurate databases of digital twins for virtual analysis, conservation, and visualization in Augmented, Mixed, and Virtual Reality [13].

Simultaneously, prototyping techniques have advanced, allowing the production of physical copies of 3D models with high reliability and low cost [14]. The physical reproduction of digital twins serves as a resource for defining material models [15], facilitating formal analyses, introducing physical substitutions, and enabling contact study operations not possible with original works [16].

The article's research proposes a metrological comparison among a real artifact, its digital twin, the derived physical copy, and the optimized virtual model within this development framework. The objective is to verify the data translation process from physical to digital and back, evaluating the entire pipeline in terms of communicative scope and outputs. The metrological validation aims to measure the model's reliability and the overall process, establishing a tested method for defining physical copies.

2. CASE STUDY

The Mausoleum of Sant'Elena constitutes one of the most important architectural complexes of early Christian Rome in the 4th century. Built between 315 A.D. and 326 A.D., originally intended to serve as a burial ground for Constantine himself, it was later used maybe as a tomb for Flavia Giulia Elena, the emperor's mother, who died in about 329 A.D.

The marble head that is the subject of the contribution (Inv. PCAS-82) is one of the most important finds preserved in the Antiquarium of the Mausoleum of Sant' Elena, a cultural site of the Special Superintendence of Rome, reopened in 2019 after a long restoration, thanks to an agreement with the Pontifical Commission for Sacred Archaeology, which currently manages it as part of a tour that also includes the nearby catacombs of SS. Marcellino e Pietro [17], [18].

The find is a female head-portrait in Pentelic marble, 21 cm high, consisting of two matching fragments and lacking the lower part of the face and a large part of the nose. The left profile is unfinished, probably because it was not visible in the original location. The hairstyle is 'turban-like,' with a large plait that wraps around the hair, divided by a central parting and folded in regular waves that descend to the nape, hiding the ears. The expression on the face is firm, severe, and slightly abstract, thanks to the fixity of the gaze. All the features seem to lead back to the Constantinian iconography of Elena, mother of the emperor

Figure 1. Head of Sant'Elena.

Constantino, based on both stylistic comparisons and the provenance of the find, which can be linked to the 1976 excavation in the M5-M8 galleries of the catacombs of SS. Marcellino e Pietro [19].

The studies on the artifact, which will be illustrated below, authorized by the Pontifical Commission, are part of some works promoted in 2021 by the Special Superintendence of Rome to complete the Antiquarium of the complex and facilitate its accessibility (Figure 1).

The contribution examines the outcomes of an experiment focused on generating a physical copy designed for tactile enjoyment. The development of the digital twin aligns with Italian regulations that restrict the creation of copies using contact methodologies. Consequently, the utilization of metrological surveying tools and 3D printing presents a compelling alternative for constructing artifacts intended for multisensory use.

3. THE SURVEY

The approach utilized in the study incorporated the use of digital photogrammetry and a portable 3D laser scanner equipped with fringe projection and metrological features, specifically designed for capturing small objects.

3.1. Sfm methodologies

The Structured from Motion (SfM) methodology proves to be an efficient solution in terms of both time and logistical considerations. The ability to capture a significant number of photographs enables the generation of highly detailed models, such as point clouds with a resolution even below one-tenth of a millimetre, making them compatible with predefined threshold values. The application of this methodology facilitated the creation of a point cloud model that adhered to the specified

Figure 2. Point cloud model obtained with sfm methodologies.

Figure 3. Point cloud model obtained with structured light scanner

design threshold values. Scaling of the point cloud was achieved through a cloud-to-cloud comparison with a model of known reliability, obtained using a structured light scanner with an accuracy of 0.1 mm and a resolution of (0.2 × 0.2) mm. However, the construction of the interpolation mesh surface from the point cloud highlighted the limitations of this method, particularly due to the presence of significant noise, especially in areas with smooth original surfaces (Figure 2).

3.2. Structured Light Scanner

A second survey was conducted using a handheld structured light scanner with a point accuracy of 0.1 mm and the capability to generate a point cloud with a mesh size of (0.2 × 0.2) mm. Employing this tool facilitated the creation of a reliable and metrically accurate model, meeting the precision requirements of the study. Examination of the point cloud resulting from the scanning process revealed a nearly complete absence of noise, positively influencing the subsequent mesh surface processing. The optimal outcomes were observed in defining smooth surfaces, as the instrument adeptly recognized and discretized them with minimal noise (Figure 3).

Due to its geometric characteristics, the models derived from the dataset obtained through this tool, encompassing both point

Figure 4. New original made with 3D printer after the “scialbatura”.

cloud and mesh, were designated as the Gold Standard in validating the results throughout various phases of the research.

Capitalizing on the superior quality of the mesh surface, the model generated from the structured light scan data was utilized in the 3D printing stage for crafting the new original.

4. THE COSTRUCTION OF THE COPIES

After establishing the digital mesh model of the original object, the physical model was produced (Figure 4) through 3D printing. Among the various 3D printing technologies, filament printing was chosen, utilizing a Delta Wasp 4070 loaded with white PLA, extruded through a 0.4 mm nozzle, and configured to generate 0.2 mm slices. The preference for filament printing technology stemmed from its current capability to replicate objects of substantial size, as highlighted by the market analysis of 3D printers which today can reach large dimensions (maximum size currently achievable 1 m × 1 m × 1 m) only by exploiting this specific printing technology.

Once the PLA copy was fabricated, it underwent a lapping process involving a mixture of calcium carbonate and resin applied with a brush to eliminate the characteristic ridges produced during the slicing process. This procedure resulted in the creation of a “new original,” enabling the application of traditional techniques for copy construction through contact. Specifically, a mold was fashioned using silicone rubbers that adhered seamlessly to the surface of the new original, creating a negative for constructing the final copy (Figure 5).

With the silicone rubber made and the mold reconstructed, the physical copy was crafted through casting, using a cement-based mixture chosen to achieve the desired material effect, simulating the original material (Figure 6).

5. METHODOLOGY AND RESULTS

The creation of the initial accurate digital twin (Gold Standard) using a structured light 3D laser scanner initiated various comparisons between virtual models and physical ones obtained through different techniques. This approach enabled

Figure 5. Negative model of the new original made of silicone.

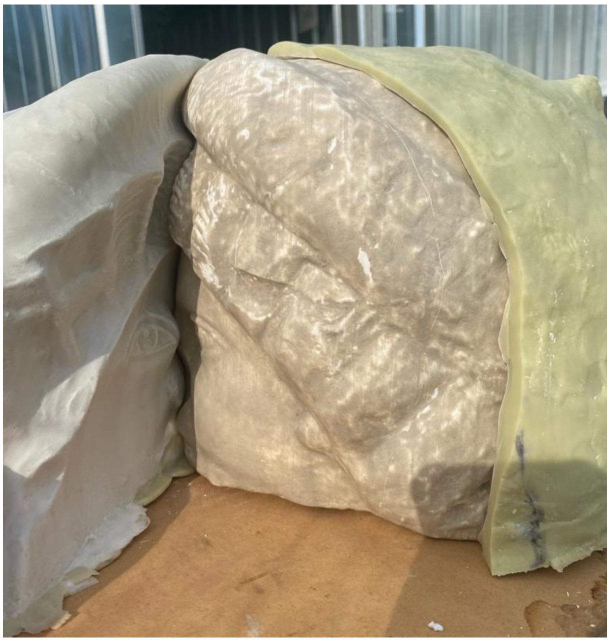

Figure 6. Extraction of the new cast model from the silicone counter-mould.

the assessment of data accuracy and reliability at each stage while adhering to specific tolerances defined by the superintendency.

The experimental results primarily focused on the metrological verification of different copies of the artifact.

The analysis highlighted how in terms of accuracy, for the GS we can refer to that provided by the instrument's technical data sheet and taking into account the variable acquisition distance it can be assumed to be equal to 0.2 mm on the point. To validate the different models, the comparison method was used to evaluate the standard deviation which, as highlighted in the Table 1, is always less than one mm compared to the GS.

Through comparisons with the original artwork, the following validations were achieved: The metrological correspondence of the copy, created with a 3D printer and optimized through the "scialbatura" process, establishes it as the new original for making contact copies. The copy, made with a cement-based mixture of marble aggregate, is designed for tactile enjoyment.

Verification of different non-contact acquisition techniques, comparing results from photogrammetric methods (SfM) versus 3D laser scanner techniques, with a critical evaluation of the quality of the surfaces obtained.

Table 1. Comparison table.

Comparison	Accuracy	Max deviation	Standard deviation
GS	0.02 mm		
GS-Sfm		1.1 mm	1 mm
GS-PLA		1.3 mm	1 mm
GS-Resin Cast		1.3 mm	1 mm

Metric comparisons between surveyed models revealed specificities related to the manufacturing process and the definition of models, with overall variations less than a millimeter.

Specifically:

- Comparison between the Gold Standard (GS) model, surveyed with the 3D scanner, and the photogrammetric model of the original demonstrated a good distribution of detachment, with greater values around the face.
- The GS versus the 3D laser scanner scan of the PLA version (template for the cast model) exhibited higher overall reliability than other copies, considering it as a new original for subsequent processing.
- Analysis of the data obtained by comparing with the GS revealed a concentration of errors at the model's base, attributed to the scanning process and digital reassembly.
- The GS versus the 3D laser scanner model of the cast resin copy showed excellent correspondence in the front part of the head, with variations at the base and parts of the hair attributed to differences between the GS and the PLA head, as well as the manufacturing process of the silicone matrix for the new copy.

Overall, the comparisons demonstrated the reliability of both methodologies for acquiring casts and physical copies, confirming the validity of the non-contact production process capable of producing geometrically reliable copies (Figure 7).

The process of verifying the trustworthiness of the physical and digital copies shown is a prerequisite for using the phygital twins for communication purposes. This makes it possible to validate the geometric quality of the model in terms of its distance from the original, allowing, on the one hand, the production of reliable physical twins and the strict relation between virtual and real artifacts, also evaluating, if necessary, the optimization of the model topology for specific communication applications.

6. CONCLUSIONS

The paper encompasses several objectives within the realm of digitization processes for Cultural Heritage. Notably, it addresses challenges such as rapid prototyping techniques and the potential for disseminating artifacts in a multisensory format, contributing significantly to the preservation and communication of Cultural

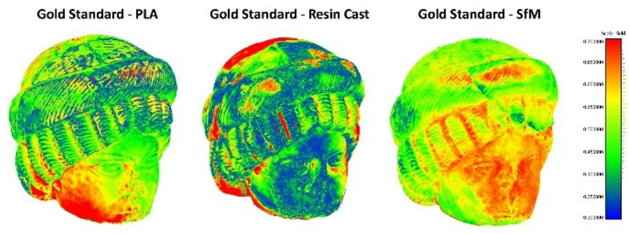

Figure 7. Comparison between models.

Heritage. The creation of copies emerges as a valuable strategy, offering excellent opportunities to broaden the user base and enhance the museum experience for new audiences.

The contribution aligns with this context by leveraging technologically advanced proposals, subject to scientific evaluation, to expand the communication capacity of specific artworks. While the market already provides various solutions for the multisensory and web fruition of Cultural Heritage, the paper emphasizes the importance of a scientific approach that considers the intrinsic quality of the copies. This approach is crucial for ensuring the proper realization and study of the asset. By operating in this manner, the artwork can be appreciated and studied directly through its twins.

The metrological verification in this type of study constitutes a fundamental element for the validation of the results but above all of the procedures used in a logic of advancement and qualitative improvement of the products.

In the future, the topic can be further expanded to address the issue of texture optimization, adding another layer of complexity and refinement to the scientific exploration and understanding of Cultural Heritage.

REFERENCES

[1] F. Bernardini, H. Rushmeier, I. M. Martin, J. Mittleman, G. Taubin, Building a digital model of Michelangelo's florentine pieta, IEEE Comput. Graphics Appl. 22(1) (2002), pp. 59-67.
DOI: 10.1109/38.974519

[2] M. Levoy, K. Pulli, B. Curless, S. Rusinkiewicz, D. Koller, L. Pereira, M. Ginzton, S. Anderson, (+ 4 more authors), The Digital Michelangelo Project: 3D scanning of large statues, Proc. of ACM SIGGRAPH, New York, 2000, pp. 131–144.
DOI: 10.1145/344779.344849

[3] G. Godin, J. A. Beraldin, J. Taylor, L. Cournoyer, M. Rioux, S. El-Hakim, R. Baribeau, F. Blais, (+ 3 more authors), Active optical 3d imaging for heritage applications, IEEE Comput. Graphics Appl. 22(5) (2002), pp. 24-36.

[4] B Curless, S Seitz, JY Bouguet, P Debevec, M Levoy. 3D Photography. Course Notes for SIGGRAPH, 2000. Online [Accessed 12 August 2024]
http://www.cs.cmu.edu/~seitz/course/3Dcontents.pdf

[5] F. Remondino, A. Guarnieri, A. Vettore, 3D modeling of close-range objects: photogrammetry or laser scanning?, Proc. of SPIE 5665, Videometrics VIII, 2005, 56650M.
DOI: 10.1117/12.586294

[6] G. Guidi, B. Frischer, M. Russo, A. Spinetti, L. Carosso, L. L. Micoli, Three-dimensional acquisition of large and detailed cultural heritage objects, Machine Vision and Applications 17(6) (2006), pp. 349-360.
DOI: 10.1007/s00138-006-0029-z

[7] A. Mathys, J. Brecko, D. Van den Spiegel, P. Semal, 3D and challenging materials, Digital Heritage 1 (2015), pp. 19-26.
DOI: 10.1109/DigitalHeritage.2015.7413827

[8] C. Nicolae, E. Nocerino, F. Menna, F. Remondino, Photogrammetry applied to problematic artefacts, Int. Arch. Photogramm. Remote Sens. Spatial Inf. Sci. 40(5) (2014), pp. 451–456.
DOI: 10.5194/isprsarchives-XL-5-451-2014

[9] S. Bi, Y. Chang, L. Chang, C. Jun, W. Wei, C. Yueri, A Survey of Low-Cost 3D Laser Scanning Technology, Applied Sciences 11(9) (2021), p. 3938.
DOI: 10.3390/app11093938

[10] A. Calantropio, G. Patrucco, G. Sammartano, L. T. Losè, Low-cost sensors for rapid mapping of cultural heritage: first tests using a COTS Steadicamera, Appl. Geomat. 10 (2018), pp. 31-45.
DOI: 10.1007/s12518-017-0199-6

[11] T. P. Kersten, M. Lindstaedt, Image-Based Low-Cost Systems for Automatic 3D Recording and Modelling of Archaeological Finds and Objects, in: Progress in Cultural Heritage Preservation, EuroMed 2012, M. Ioannides, D. Fritsch, J. Leissner, R. Davies, F. Remondino, R. Caffo (editors). Springer Berlin, Heidelberg, 2012, ISBN 978-3-642-34234-9.
DOI: 10.1007/978-3-642-34234-9_1

[12] R. Ravanelli, A. Nascetti, M. Di Rita, L. Nigro, D. Montanari, F. Spagnoli, M. Crespi, 3D modelling of archaeological small finds by a low-cost range camera: methodology and first results, Int. Arch. Photogramm. Remote Sens. Spatial Inf. Sci. 42(5) (2017), pp. 589-592.
DOI: 10.5194/isprs-archives-XLII-5-W1-589-2017

[13] G. Guidi, S. Gonizzi Barsanti, L. L. Micoli, M. Russo, Massive 3D Digitization of Museum Contents, in: Built Heritage: Monitoring Conservation Management, L. Toniolo, M. Boriani, G. Guidi (editors). Research for Development, Springer Cham, 2015, ISBN 978-3-319-08533-3.
DOI: 10.1007/978-3-319-08533-3_28

[14] C. Balletti, M. Ballarin, F. Guerra, 3D printing: State of the art and future perspectives, Journal of Cultural Heritage 26 (2017), pp. 172-182.
DOI: 10.1016/j.culher.2017.02.010

[15] L. J. Senatore, B. Wielich, Modelli tattili per la conoscenza. Eros che incorda l'arco al Parco Archeologico di Ostia Antica, in: Atti del Convegno DAI 2022, Genova 2-3 dicembre 2022, C. Candito, A. Meloni (editors), DAI il Disegno per l'Accessibilità e l'Inclusione. Publica Edizioni, 2022, ISBN 987799586256, pp. 716-729. [In Italian].

[16] M. Russo, L. J. Senatore, Low-cost 3D techniques for real sculptural twins in the museum domain, Int. Arch. Photogramm. Remote Sens. Spatial Inf. Sci. 48(2) (2022), pp. 229–236.
DOI: 10.5194/isprs-archives-XLVIII-2-W1-2022-229-2022

[17] R. Bochicchio, Il Mausoleo di Sant'Elena. Il monumento e l'Antiquarium. Milano, Italy, 2019. [In Italian]

[18] R. Giuliani, SS. Marcellino e Pietro, Catacombe di Roma e d'Italia 11. Città del Vaticano, 2015 [In Italian].

[19] R. Giuliani, Un ritratto ritrovato dell'Augusta Elena dal complesso ad duas lauros?, in: Costantino e i Costantinidi. L'innovazione costantiniana, le sue radici e i suoi sviluppi, O. Brandt, V. Fiocchi Nicolai (editors). Acta XVI Congressus Internationalis Archaeologiae Christianae (Rome, 22-28/9/2013), PIAC, Città del Vaticano, 2016, pp. 879-893. [In Italian]