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DIGITAL TWINS OF ARCHAEOLOGICAL FINDS: OPEN SOURCE TECHNOLOGIES APPLIED TO 3D SCANNING

1. Introduction

This article aims to analyze the complex issue of 3D documentation of archaeological artifacts under various perspectives: from possible technologies to current methodological limitations, in light of the results obtained. These results will be described based on direct experiences derived from specific archaeological projects, whose primary purpose was indeed the creation of digital twins of selected artifacts. Among the institutions involved in such projects are the MArTA (Museo Archeologico Nazionale di Taranto), the South Tyrol Museum of Archaeology, and the UMSt (Unità di Missione Strategica) of the Soprintendenza per i Beni e le Attività Culturali of the Autonomous Province of Trento (PAT).

2. Projects and institutions involved

2.1 *MArTA*

MArTA is an Italian State Museum that houses a vast collection of artifacts from the Apulian region. It displays one of the largest collections in the world of artifacts from the Magna Graecia period and is famous for the so-called 'Ori di Taranto', a collection of jewelry and precious ornaments from the Hellenistic and Roman periods. Between 2020 and 2022, as part of the MArTA 3.0 project (aimed at digital enhancement of the museum), a cataloging effort of 40,000 artifacts, oriented towards open data dissemination, was initiated. Within this project, the artifact record sheet, compiled by the company ArcheoGEO, and their photographs were integrated into an open source webGIS, specifically developed by the company Arc-Team. Among the 40,000 artifacts registered, MArTA researchers selected 100 of the most interesting archaeological finds to enrich their respective record sheets with a 3D digital twin.

This final phase of the project allowed testing of various 3D documentation techniques on a wide range of artifacts, whose extreme variability was evident in their dimensions, methods of museum display, complexity of shapes, and richness of materials.

2.2 *South Tyrol Museum of Archaeology*

The South Tyrol Museum of Archaeology is world-renowned for housing the famous Similaun mummy, also known by the nickname Ötzi. In addition to the mummy, the museum houses significant archaeological collections from the Autonomous Province of South Tyrol, ranging from the Copper Age to the Middle Ages. In 2023 Arc-Team was commissioned for the 3D scanning of the artifacts discovered in 1991 along with the Similaun mummy. This project aimed to create digital twins for both research and conservation purposes. The experience allowed for a significant number of digital replicas of artifacts, mainly composed of organic materials, using not only established documenting techniques based on Structure from Motion (SfM) but also experimental methodologies based on the innovative approach of Artificial Intelligence (AI), supported by neural networks using NeRF (Neural Radiance Field) algorithms. This experience led, in 2024, to the 3D scanning of the Similaun mummy itself, obviously carried out in the protected environment of a climate-controlled room at a temperature of -6° C.

2.3 *UMST*

UMST is an entity of PAT, which, through the Office of the Soprintendenza per i Beni e le Attività Culturali, is responsible for the study, protection, conservation, and enhancement of the Cultural Heritage of Trentino. Within its responsibilities, UMST also oversees the scientific direction of archaeological excavations and, therefore, the 3D documentation of the investigated sites and artifacts. Given the peculiar territory of a province like Trento, largely mountainous, the task of UMST also includes investigating archaeological realities related to 'hidden heritage' contexts, which are difficult for the public to access and also challenging for specialists (professionals) tasked with various analyses. This type of mission falls within the branch of extreme archaeology and can involve glacial or high mountain contexts, as well as underwater (lakes and rivers) and hypogeal (caves and galleries) environments. Examples include research projects in underwater archaeology, such as the one studying the submerged forest of Lake Tovel since 2005, or speleo-archaeological projects, such as the one investigating the depositional context of the human remains found in the 'Grotta del Teschio' (Skull Cave) on Monte Stivo since 2023. This latter project has been supported by 3D SfM techniques, once again proving crucial for the successful outcome of the research, thanks also to their great versatility.

3. Case studies

3.1 *Variability of artifacts: the MArTA collection*

The case study involving the 3D scanning of 100 selected artifacts from MArTA collection, although initially based on SfM techniques (Bezzi *et al.* 2011), allowed for exhaustive testing of other technologies, which, as anticipated, proved ineffective for artifacts that were more challenging to scan, particularly those with reflective surfaces such as metals and, above all, gold. The project encompassed a wide range of artifacts from prehistory to the Roman period and, specifically, 26 stone statues of varying sizes and lithotypes (including the famous head of Hercules, possibly inspired by the sculpture of Lysippus), 1 bronze statuary element (the renowned Zeus of Ugento), 20 items of ceramic vessels (ranging from Apulian to Greek, featuring both red-figure and black-figure pottery, such as Panathenaic amphorae), 16 terracotta elements (gladiator figures, 'recumbent' characters, matrix molds, theatrical masks, acroteria, and miniature models), 6 stone architectural elements (primarily capitals, bases, and funerary markers), 12 gold and, more rarely, silver jewelry items (earrings, bracelets, crowns, scepters, and mirrors), 2 glass objects (a bird figurine and a cinerary urn), 9 bronze artifacts (ranging from everyday objects, like bowls and pans, to military-related items, like helmets, as well as decorative objects, like the famous nutcracker), 6 bone or horn elements (from prehistoric idols to *fibulae*), and a miniature amber statuette.

Parallel to Arc-Team's work, a second 3D scanning project was carried out by the MArTA Lab, the museum's in-house digital craftsmanship laboratory (FabLab), managed by the company PaLEoS. This second project involved the documentation of another hundred pieces using 3D scanners, which, however, were not suitable for recording artifacts with highly reflective surfaces. Indeed, this category of artifacts was not considered during the scans performed by PaLEoS. For methodological rigor, Arc-Team also briefly tested the structured light 3D laser scanning solution (Artec Space Spider), which, although comparable to SfM in terms of the precision/accuracy ratio, proved entirely inadequate, as expected, for highly reflective objects. Additionally, there were greater difficulties in capturing objects with strong undercuts due to the instrument's reduced maneuverability.

For this reason, the entire acquisition project carried out by Arc-Team was based, as initially planned, on open source SfM techniques (via MeshRoom, openMVG/OpenMVS), which allowed for the recording of all artifacts, including those that proved challenging (if not impossible) to document using alternative methods: highly reflective objects, artifacts immovable from display cases, and those with unique characteristics that required both 'external' and 'internal' documentation. Contrary to what one might think, among these archaeological finds there are no transparent or semi-transparent materials, as the two glass artifacts selected for documentation were heavily opaque due to the naturally formed patina over the centuries and thus did not present any particular problems during data acquisition and processing.

3.1.1 The 'Ori di Taranto'

As anticipated, among the most complex artifacts to document in the MArTA collections, the 'Ori di Taranto' must certainly be included. These archaeological finds, due to the materials they are composed of (gold and silver), present highly reflective surfaces, not comparable even to other 'shiny' objects, such as Greek ceramics and bronzes. While for these latter categories, it has often been sufficient to use photographic boxes, eliminating reflections through a simple polarizing filter, for the gold items it was necessary to develop a more complex strategy. Excluding, for obvious reasons, the possibility of covering such artifacts with an opaque powder (a method mainly used during laser scanning), it was decided to use the PLP technique (Polarized Light Photography), well-established in the field of Cultural Heritage (especially for painting photography), adapting it to SfM and optimizing it to the 'extreme' choice of operating in a completely controlled light environment. To do this, it was necessary to set up an emergency photographic laboratory, always within the museum perimeter (for security reasons), adapting the only room where it was possible to

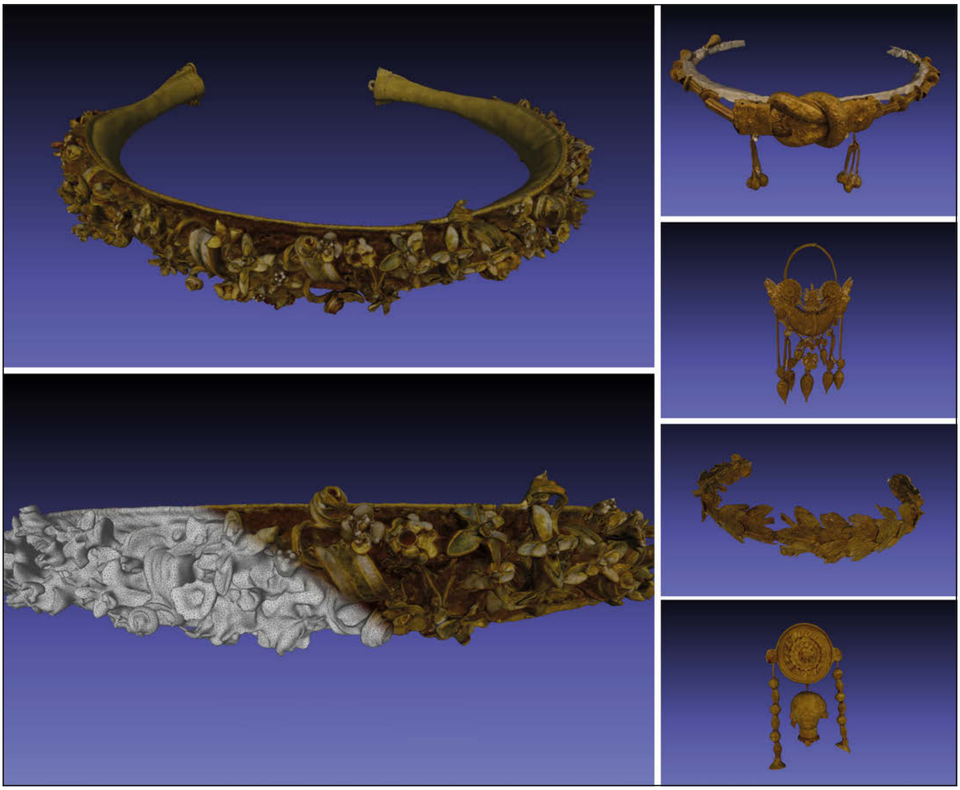

Fig. 1 – Some 3D models of the 'Ori di Taranto'.

completely eliminate external light without affecting visitor paths, maintaining a single zenithal light source and polarizing it through a special film. This inevitably led to limiting the working area to about 2 square meters, allowing the intervention of only one operator at a time.

The photos collected in this way, thanks to an additional polarizing filter on the camera lens (to eliminate specular light), proved to be almost entirely reflection-free and were processed directly, without the need for further interpolations, which were initially planned to divide each photo into a specular light image and a diffuse light image (in order to use only the latter for processing via SfM). This *modus operandi* thus led to a simplification of data processing, yielding good results. The main difficulties were encountered in 3D documenting hanging jewelry, such as the famous 'Boat shaped earing', as the vibrations from external traffic (bus passage) were felt even at the museum's third floor, making it particularly challenging to acquire optimal photos due to the micro-oscillations of the objects. Documenting the scepter of the so-called 'Opaka princess of Canosa' was also very complex, both due to the plexiglass support on which the perforated golden sheet handle was restored, and due to the dimensions of the object itself, which, given the narrow spaces, required close shots, difficult to process for SfM software due to the repetitiveness of the ornamental motif.

In this particular case, an additional 3D modeling intervention (within Blender), based on photographic documentation, was necessary to adjust the gaps that occurred in some areas of the handle. However, given the difficulty of the documentation and the good level of precision/accuracy achieved even in artifacts with more sub-squares (such as the flowered diadem of the 'Tomb of the Gold'), the acquisition via SfM of the 'Ori di Taranto' was considered adequate, based on the archaeological tolerance established for the project (Fig. 1).

3.1.2 The 'Zeus of Ugento' and the monumental craters of Ceglie del Campo

A rather particular category of artifacts to be documented in 3D was that composed by objects that were characterized by logistical challenges determined by the impossibility of dismantling the museum installations in which they were housed. This is the case of the 'Zeus of Ugento' and, especially, of the two monumental craters of Ceglie del Campo. In the former case SfM documentation did not prove particularly difficult thanks to the manageability of a simple digital camera, which only required a polarizing filter to eliminate reflections caused by complex ambient light (also attenuated through the use of illuminators and reflective panels). By contrast, in the latter case, it was necessary to devise a strategy suitable for the particular situation of museum display. Indeed, the two craters, characterized by their large dimensions, are currently housed inside two adjacent display cases, from which they cannot

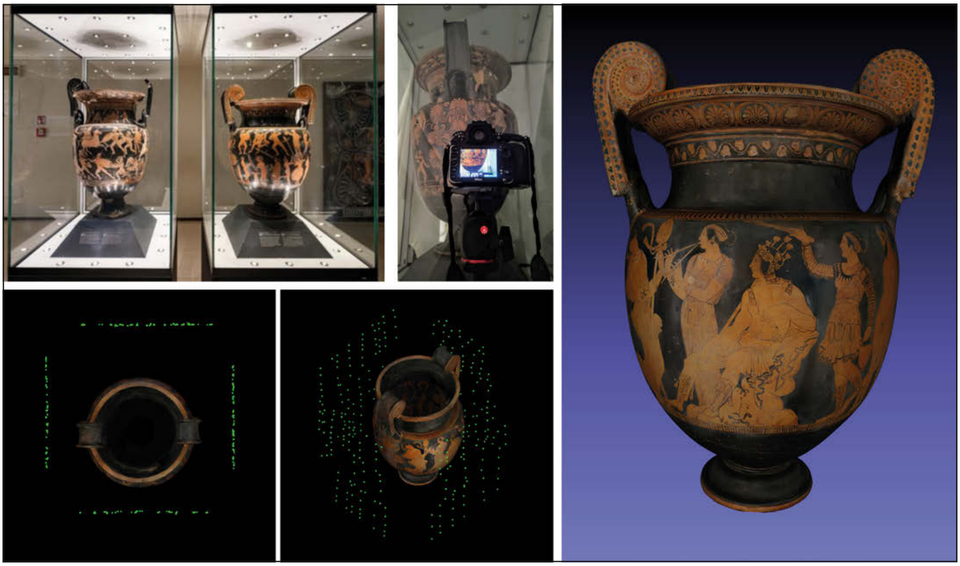

Fig. 2 – The craters of Ceglie del Campo (museum installation and 3D models with camera positions).

be removed. For this reason, discarding any possible strategy based on 3D scanners, the versatility of SfM was exploited once again.

Specifically, the display cases were covered with black cloths to eliminate ambient light (in this case unmanageable), and the 3D acquisition was conducted by placing the camera lens directly on the glass of the cases. This type of operation required an extremely regular sequence of shots, made even more complex by the passage between the two cases (spaced about 30 cm apart), greatly limiting the operator's freedom in choosing the angle and number of photos considering the morphology of the objects to be documented (fortunately, in this case, very regular). Despite this difficulty and the challenging management of light (the numerous spotlights in the display cases), the survey was successfully carried out, once again meeting the predetermined parameters (Fig. 2).

3.1.3 The terracotta model of a *nymphaeum*

Another rather unique documentation was that of a terracotta miniature model of a *nymphaeum*. In this case, the complexity of the 3D acquisition lays in the fact that, to appreciate the functioning of the artifact where water was made to spurt from a lion protome through a reservoir, a strategy capable of registering the object both externally (for the reservoir) and internally (for the lion protome), was necessary. Again, given the

Fig. 3 – The terracotta model of the *nymphaeum*.

small size of the object, any documentation through laser-scanning was out of the question, while a strategy based on SfM allowed for setting up an external acquisition with a regular camera (Nikon D800) and an internal acquisition with a camera small enough to pass through the main opening of the *nymphaeum* itself (GoPro 4). In this way, through the subsequent alignment of the two scans (in Meshlab and Blender), a digital twin of the *nymphaeum* was obtained, capable of showing both external and internal details (Fig. 3).

3.2 *Organic materials: the Similaun mummy and its artifacts*

The documentation of the artifacts preserved at the South Tyrol Museum of Archaeology was a very peculiar project, mainly focused on documenting organic materials. For this reason, some specific solutions were adopted, both in data acquisition and in their processing.

3.2.1 Ötzi's artifacts

Among the artifacts documented in 3D during the 2023 acquisition are those predominantly made of worked leather, such as the quiver (roe deer), leggings (goat), loincloth (sheep), overcoat (goat and sheep), cap (bear),

Fig. 4 – The hat of the Similaun mummy: model adjustment through displacement mapping (left) and comparison between the NeRF model (white background) and the SfM model (black background).

the upper part of the right shoe (deer); those made of plant elements, such as the shoes (straw and lime bark) and those made of wood, such as the quiver shaft (hazelnut) and the axe (yew), whose blade is obviously made of copper. This range of artifacts did not present any particular issue in reproducing digital twins via SfM, especially considering that very few areas of the leather materials still retained fur (right leggings), often very sparse (overcoat). The only precaution in these cases was to increase the detail of the skin through the displacement mapping technique, used for the first time by Arc-Team during the Forensic Facial Approximation (FFA) of the mummy of S. Catherine of Genoa in 2018 (Bezzi *et al.* 2019). A different case was the hat, where the fur covering the leather cap is still very dense. For this reason, alongside the traditional SfM processing, an experimental documentation was conducted using the open source software Nerfstudio (Tancik *et al.* 2023), which integrates Computer Vision with Artificial Intelligence techniques. In other words, this application allows the use of NeRF algorithms (CGI), which model the relationship between light rays and pixel colors in the 3D scene, using neural networks (AI), and, starting from an initial SfM survey, reconstructs and enhances the perception of the 3D scene, allowing the generation of realistic images from any angle without actually capturing data from multiple perspectives. Obviously, this is a 'partially reconstructive' method, but one that builds upon solid foundations and, in the case of the artifact in question, has allowed for the recording of a good dataset, capable of providing a photorealistic rendering of the artifact itself from any angle, enabling restorers to monitor any degradation over time. In other words, the extremely high detail achieved are capable of realistically representing the fur covering better than the 3D SfM model (much less detailed). In essence, it was an integrative experimental method (compared to the 3D survey in the strict sense), which met the conservative requirements (Fig. 4).

3.2.2 The Similaun mummy

The case of the 3D documentation of the Similaun mummy performed in 2024 is a bit too complex to be exhaustively covered in this article. However, it is possible to briefly mention the technical precautions that were necessary during the data acquisition and the planned (and ongoing) post-processing methodology for the production of a digital twin of the mummy that combines photogrammetric and radiological (CT scan) models. Regarding the initial phase, the photographic acquisition, once again PLP applied to SfM, was used in an environment where it was not possible to control artificial lighting, namely the climate-controlled backup room where the work was conducted. For this reason, a strategy based on polarizing the light emitted by the ring LED attached to the camera was implemented, capable of counteracting and covering ambient light, whose reflections were eliminated by the polarizing filter of the lens, suitably aligned. The post-processing phase, on the other hand, was characterized by adjustments that had to resolve the alignment problem of the front and back of the 3D documentation of human remains, which, although frozen at a temperature of -6°C, assume slightly different positions once moved.

For this reason, the technique of 'coherent anatomical deformation', developed by Arc-Team in 2012 for the field of FFA (Bezzi 2016), was used, adapting one 3D model to another according to precise and controllable parameters. Once the photogrammetric digital twin of the Similaun mummy (with high-resolution textures) is obtained, the technique of coherent anatomical deformation will be used again to adapt it to the voxel model of the CT scan (devoid of color) and produce a single model that combines both radiological and colorimetric data.

3.3 *3D documentation on the field*

Up to this point, only 3D documentation carried out in protected environments (such as laboratories and museums) have been described. This final chapter will focus on surveys carried out in the field in challenging environments, related to the branch of extreme archaeology, focusing on the most recent case of speleo-archaeology followed by UMST: the 'Grotta del Teschio'.

3.3.1 The documentation of 'Grotta del Teschio'

Towards the end of 2023, Arc-Team was commissioned to carry out a speleo-archaeological excavation inside a cave where human remains had

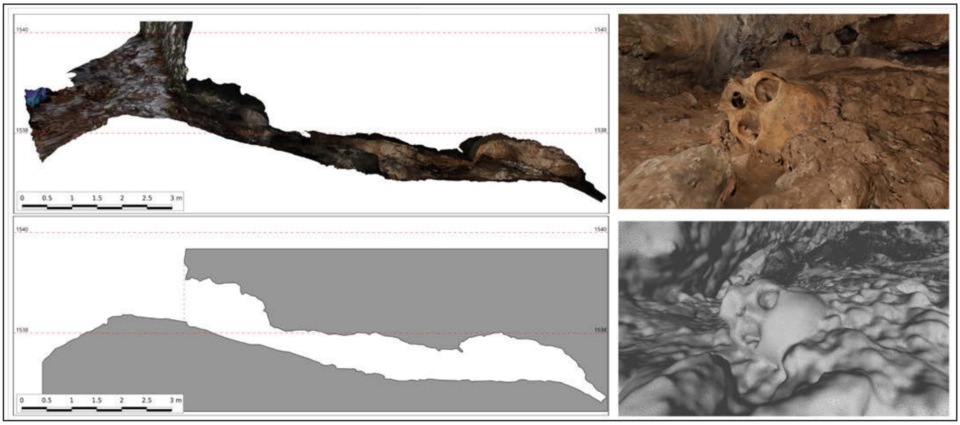

Fig. 5 – The 3D of 'Grotta del Teschio': general model and detail of the skull.

recently been discovered: the 'Grotta del Teschio'. For obvious reasons, before the actual excavation began, a 3D documentation of the entire underground environment was conducted using SfM, in order to record the exact position of every find, human or otherwise. The strategy adopted was chosen due to the excellent results achieved in previous years with photographic acquisitions in extreme contexts (underwater, underground, and glacial). In this specific case, the great versatility of a technique based on photography allowed for smooth operation in narrow environments where it would not have been possible to penetrate with bulkier equipment, while also ensuring the correct registration of metric and geographic values thanks to the use of Ground Control Points (GCP) located outside the cave entrance and recorded with differential GPS. The level of accuracy and precision achieved with the 3D documentation of the 'Grotta del Teschio' supported the stratigraphic excavation of the environment with precise 3D of each individual find *in situ*, awaiting possible integration following the study and restoration of the recovered objects (Fig. 5).

4. Conclusions

The projects presented thus far, characterized by a wide range of materials, logistical conditions, and different challenges, have highlighted the limitations that many three-dimensional documentation methodologies may encounter in practice, particularly those based on laser scanning. Considering the experiences proposed, the only reliable methodology in particularly challenging contexts has proven to be that based on SfM and this not so much for the quality of the results obtained, but for the versatility of the methodology itself. Essentially, all the issues that emerged during the individual projects presented were easily resolved thanks to the ability to intervene either during photo acquisition (through appropriate polarizing filters or through the use of different cameras) or during processing, using various software and algorithms. Furthermore, at present, SfM has proven to be highly compatible with the new NeRF methodologies, which seem rather promising for the study of Cultural Heritage.

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REFERENCES

Bezzi A., Bezzi L., Ducke B. 2011, *Computer Vision e Structure from Motion, nuove metodologie per la documentazione archeologica tridimensionale: un approccio aperto*, in G. De Felice, M.G. Sibilano (eds.), *ArcheoFOSS: Open Source, Free Software e Open Format nei processi di ricerca archeologica. Atti del V workshop (Foggia 2010)*, Santo Spirito, Edipuglia, 103-111.

Bezzi L. 2016, *FACCE. I molti volti della storia umana*, «Blender Magazine Italia», 18, 10-13.

Bezzi L., Bezzi A., Moraes C. 2019, *Ricostruzione facciale forense di S. Caterina Fieschi Adorno. Relazione tecnico-scientifica* (https://doi.org/10.13140/RG.2.2.23780.19844).

Tancik M., Weber E., Ng E., Li R., Yi B., Kerr J., Wang T., Kristoffersen A., Austin J., Salahi K., Ahuja A., McAllister D., Kanazawa A. 2023, *Nerfstudio: A modular framework for neural radiance field development*, in E. Brunvand, A. Sheffer, M. Wimmer (eds.), *Proceedings SIGGRAPH 2023 Conference Papers (Los Angeles 2023)*, Proceedings Production Editor, art. 72.

ABSTRACT

This article aims to analyze the complex issue of 3D documentation of archaeological artifacts under different viewpoints: from potential technologies to current methodological limitations, in light of the obtained results. These results will be described based on direct experiences derived from specific archaeological projects, whose primary aim was indeed the

creation of digital replicas of selected artifacts. Among the institutions involved in such projects are the MArTA (Museo Archeologico Nazionale di Taranto), the South Tyrol Museum of Archaeology, and the UMST (Unit. di Missione Strategica) of the Soprintendenza per i Beni e le Attività Culturali of the Autonomous Province of Trento (PAT).