2023 IMEKO TC-4 International Conference on
Metrology for Archaeology and Cultural Heritage
Rome, Italy, October 19-21, 2023

The survey of the 'precious ones of Constance'. Tools and techniques for three-dimensional restitution of complex surfaces at sub-millimetre resolution

Francesco Di Paola[1], Sara Morena[1], Giulio Raimondi[1], Sara Antinozzi[2]

[1]*Dept. of Architecture, University of Palermo, p.zza Marina 61, 90133 Palermo (PA), Italy, francesco.dipaola@unipa.it, sara.morena@unipa.it,giulio.raimondi@community.unipa.it*
[2]*Dept. of Civil Engineering, University of Salerno, via Giovanni Paolo II 132, 84084 Fisciano (SA), Italy, santinozzi@unisa.it*

I. INTRODUCTION

The digital reproduction of cultural artefacts is a challenging task and should not be underestimated today. The great variety of objects and the complexity of textures that characterise them inevitably necessitate the delineation of even more precise and specialised studies. Numerous factors must be managed to ensure high quality and accuracy of sub-millimetre resolution models. The key issues concern the purpose of the survey and the associated data dissemination, timing, instrumentation and expertise available. In addition to the listed aspects, there are inherent typological factors of the wide and diversified cultural heritage: specific and unique characteristics of each artefact – related not only to the small size, but also to the constituent material – cause even more reproducibility difficulties, due to reflective, translucent and/or excessively homogenous surfaces [1]. Lastly, the boundary conditions in terms of the opportunity to work in controlled environments and to move artefacts freely.

This study reports two examples of surveying objects of accentuated complexity: "the precious ones of Constance" (Figure 1). These are emblematic cases selected to determine whether the recording systems chosen, a structured light scanner and a low-cost camera integrated into a USB microscope, could support the requirements of accurate and reliable three-dimensional reconstruction. The first one is the Crown of Constance of Aragon, the second one is a couple of earrings, the so-called earrings "of Costance".

The Crown of Constance of Aragon, currently kept in the Cathedral Museum in Palermo, is a filigree cap of gilded silver with pearls and precious stones set in it and two side pendants. Its materials include gold, gilded silver, silk, enamels, pearls, precious stones such as garnets, rubies, sapphires, topazes, and on the top an ovoid amethyst. Also known as "kamelaukion", it was probably initially used by Frederick II in his own coronation ceremony (1220), which has raised some questions as to why it was in the sarcophagus of Constance of Aragon. The most popular thesis is that it had been worn in turn by the Queen of Sicily for her coronation as empress, and the crown and gown were part of a coordinated apparatus executed by the royal atelier as part of the Sicilian goldsmith tradition [2]. The object was found in Constance's sarcophagus when it was inspected in 1491. During the multiple restorations, the inner iron frame (which served to keep it rigid but had oxidized and ruined the fabrics) was removed, and the ruined fabrics were reinstated, and the beads were restrung.

Fig. 1. On the left: the Crown of Constance of Aragon. Palermo, Cathedral Museum; on the right: the so-called earrings "of Constance". Palermo, Regional Gallery of Sicily.

The so-called earrings "of Constance" [3] of gold filigree come from Palazzo Abatellis, from the collections of the National Museum and are preserved in Palermo at Regional Gallery of Sicily. Their designation is as it is not because they come from that tomb but rather because they are a late product from the manufacture of the Royal Palace in Palermo, probably from the end of the reign of Guillermo II, close, in terms of technical solutions, to certain parts of the Crown of Constance. Among the characteristics of the goldsmith's work is the filigree, preferred to gold foil, with its refined chiaroscuro effects given by the solids and voids that soften the luminous effect, reproposing the widespread basket type found in Byzantine examples such as those dating from the 6th century [4]. The type of bird heads with hooked beaks, of Byzantine inspiration, can also be seen in the enamels that adorn Roger II gloves (Vienna, Kunsthistorisches Museum). The paired bird motif is also present in the half-moon earring in the Archaeological Museum in Syracuse, from the Byzantine tomb of Racineci. It is therefore possible to highlight how significant was the influence, not only typologically but also stylistically and iconographic, of Byzantine art in Palermo even at the end of the Norman period.

Both exhibits are precious and delicate, characterised not only by small elements but also by reflective materials that make them particularly difficult to acquire. Furthermore, in the case of the crown, these elements are distributed over the entire surface of the headgear, which means that micrometric resolution must be guaranteed over an extraordinarily large area. Hence, due to the specific differences of the two objects, it was necessary to test two separate technologies: a handheld structured light scanner, the Artec Spider, for the three-dimensional survey of the crown and a photogrammetric approach, using the Dino-Lite USB microscope, for the earrings. The idea was to obtain a faithful digital copy of these two exceptional artefacts in the wake of the push to digitise heritage outlined by the "The National Recovery and Resilience Plan" (PNRR), approved in 2021 for a green and digital development of Italy. One of the strategic axes of the plan is, in fact, the "digitisation and innovation" of processes, products and services, factors recognised as fundamental for improving Italian competitiveness [5]. This shows a desire to regain lost ground in terms of digital adoption and technological innovation, as highlighted by the plan itself: Italy would rank 24th out of the 27 EU Member States according to the DESI (Digital Economy and Society Index), which monitors the digital performance and progress of EU member states in terms of digital competitiveness at European level. Alongside this, in the case of the photogrammetric experiment, there is – in addition to the will to obtain a highly resolute model – the desire to verify the effectiveness of a scanning system with a cost of approximately 1/20th of the more established structured light scanner.

II. STATE OF THE ART

The above considerations paint a complex picture in which the large demand of high-quality three-dimensional models clashes with the limited affordability of a highly specialised offer. In fact, considering the field of industrial metrology, appropriate techniques and instruments for the rigorous description of small objects have been identified and consolidated over time [6-8]. However, it is not sure that these can be successfully applied to the cultural heritage area, both due to typological issues (it is not always a case of instrumentation that measures without contact and/or returns a texture datum) and different budget constraints. Generally, highly specific applications, e.g., dimensional inspection, quality control, industrial design, testing and reverse engineering of micro components, lean towards active sensor technologies because they are considered faster and often more accurate tools. Among these increasingly popular in micro-mechanics are laser triangulation systems.

A solution that has been widely used in ever more areas, thanks to its versatility and intuitiveness of use, concerns structured light scanners, optical instruments that allow three-dimensional reconstruction by projecting patterns of light onto the objects to be surveyed [9, 10]. The spread of this technology is certainly also related to the production of increasingly affordable instruments. In fact, there are currently different price ranges of instruments on the market, depending on the technical characteristics declared by the manufacturer, as well as the proprietary software combined, or to be combined, for processing the raw data.

The operating technology makes them mainly suitable for three-dimensional acquisitions of small and medium-sized objects [11] and, depending on their technical specifications, these instruments are characterised (some more, some less) by fast acquisitions and the high robustness of the data obtained, which in some cases even reach the sub-millimetre accuracy. However, due to their limited field of view, to complete a digital three-dimensional model of the object the devices might require multi-station scanning and thus it is necessary to align and process the data, which inevitably can affect the result by producing an increase in error and a decreased in accuracy. Another limitation is often the low resolution of the camera, associated with the instrument, required for texture restitution. This can, of course, also be influenced by the surface and morphological characteristics of the object, as well as the boundary conditions and the acquiring operator. In this regard, some research focuses on correct acquisition processes, proposing data verifications [12-14], innovative processes, and improving the texture of the final model [15-17].

Alongside structured light solutions, it is possible to reflect on a competitive alternative (the photogrammetry) that, despite its age, has not experienced obsolescence, but has even evolved in relation to needs, revealing great flexibility and versatility [18]. Furthermore, the widespread diffusion and accessibility of photogrammetry, as well as the helpful contribution of information technology, has made it more accessible to achieve the above-mentioned mensural purposes, especially for sectors that have recently approached very close-range surveying and that benefit most from low-cost techniques; among these, as one can easily imagine, the museal system is particularly active.

In detail, attention is focused to the segment of very close-range photogrammetry, characterised by acquisition distances of less than one metre, into which macro photogrammetry, defined by a reproduction ratio (scale of representation/actual scale) of 1:1, belongs [19]. The most conventional instrumentation for successfully conducting macro-photogrammetry would consist of a professional digital camera combined with "macro" photographic lenses, which are known to offer magnification capabilities close to the unit reproduction ratio, ensuring great incisiveness and an almost total absence of aberrations and distortions. As an alternative to macro lenses, common lenses can be adapted with specific devices, extension tubes, consisting of thick rings that are inserted between the lens and the camera body, changing the minimum focusing distance and thus allowing greater magnification at lower cost. However, a whole range of compact and lightweight cameras, such as action cameras, should not be overlooked, as well as the single-board computer disclosure the size of a credit card (Raspberry Pi), which can be combined with both entry-level and professional photo sensors and optical bodies. In addition, among the new devices that the market now makes available to satisfy this need to zoom in on the subject, are portable USB microscopes, created for inspection and two-dimensional metrological analysis and already widespread in the manufacturing industry for quality control and in the medical field. They take the form of small, handy optical zooms, designed to display image output directly on a monitor. Despite their resolution (usually up to 5MP) and small sensor size (about 1/4"), the images produced are to be considered high quality for the commercial segment in which they fit.

The scale of examples provided covers a wide instrumental range and it is not difficult to imagine that image-based alternatives require greater technical rigour. In fact, some interesting research published in the literature have a strong technical focus on dealing with the challenges of acquiring tiny objects [20-25]. Most of them centre on evaluating various photogrammetric workflows to reorganise processes while retaining high metric consistency. In these situations, many approaches are used, including camera stability, the use of rotating bases and coded targets, enhanced control over camera settings and illumination, demonstrating gains in model quality and the benefits of more monitored procedures. Further studies [26-29] focus on the management of the shallow depth of field, a characteristic of macro optics – however found, albeit with lesser effects, in all types of lenses – to limit the possible diffractive effects caused by the extreme closure of the diaphragm, a necessary choice to extend sharpness.

It was thus highlighted how the field of surveying small objects, or in any case artefacts characterised by small details, is still growing; this motivates the decision to investigate, verify and compare several useful instruments for their documentation.

III. COMPLEX SURFACES

When discussing complex (detectable) surfaces, we talk about objects that return either poor or no usable data for three-dimensional restitution due to their unstructured, monochromatic, translucent and/or reflecting characteristics [30]. As anticipated, added to these aspects, also morphological properties – as well as the work environment – may be considered to determine the general level of complexity, which in turn defines the survey design. In summary, the following variables can be used as a starting point for an analysis of the distinctive attributes of the survey:

- dimensional comparability, or the ratio between the object's X, Y, or Z dimensions, and the distribution of masses: worst-case situations include thin objects that develop mostly longitudinally or flat;
- topological complexity, which relates to the item's geometric characteristics, particularly the presence of holes or blind holes;
- logistical freedom, in terms of the potential to operate without constraints by rotating around the object or moving it freely;
- resolution ratio, which is the ratio between the maximum size of the item (for example, one can consider the average distance between the model's vertices) and the resolution of the digital model: high values indicate that greater detail is needed, resulting in higher survey complexity;
- surface complexity, impacted by geometric elements (micro-depressions, roughness, incisions, etc.), the radiometric characterization of the material, and the uniformity of the texture;
- limit of view, which is based on the presence of parts that cannot be acquired due to morphological limitations of the object itself and the fact that these elements are not always instrumentally achievable.

IV. MATERIALS AND METHODS

The first instrumentation used, as mentioned, is a 3D scanner based on structured light technology. The presence of minute decorative details directed the choice toward the Artec Spider device. It is a high-resolution 3D scanner based on blue light technology for capturing small objects or (as in this case) intricate details of large objects.

The declared 3D point accuracy is up to 0.05 mm and the ability of the scanning system to resolve details (3D resolution) is 0.1 mm. In addition, the scanner also has a texture camera that ensures the acquisition of colorimetric information characterized by a resolution of 1.3MP.

The Tracking Mode used was "Geometry + Texture" to achieve fast and accurate acquisition without necessarily using targets. The survey was quite complicated, however, the presence of geometric-formal complexity (polyhedral gemstones, carving and chiselling techniques on very small and elaborate parts) and the type of reflective materials made the acquisition process more complex and longer than usual. The object was fixed on a stable support (limiting the contact surface to a minimum) and was surveyed by rotating around it with slow and uniform movements (Figure 2). The instrument was placed orthogonally to the surface of the case study object and framed from different angles. The collected data was monitored in real-time on the notebook and visualised on the proprietary software. The survey was concluded with eleven scans, and the acquisition interruption was often caused by a tracking loss, subsequently managed during the data processing phase. Artec Studio Professional (in release 14) was the software used for the generation of the textured three-dimensional model. The software presents an intuitive and practical interface that allows good management of the settings by the operator to conduct all the different phases of the workflow. After reviewing the frames and the first editing of the several scans, "Fine Registration" and "Manual Rigid Alignment" were carried out. Subsequently, a "Global Registration" was performed, to convert all surfaces in a frame into a single coordinate system, and the final 3D model (280.969.079 polygons and 154.189.532 vertexes) was obtained with "Sharp Fusion" (0.2 mm resolution) setting. Once the mesh model was generated and edited it was possible applying texture. The Export option (Texture Atlas) was chosen to facilitate the necessary subsequent editing phases.

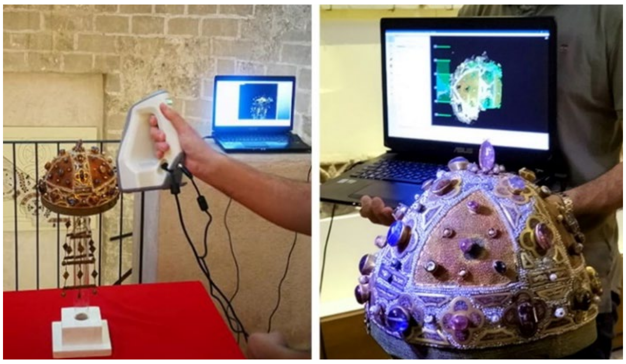

Fig. 2. The 3D handheld scanning system with a structured light flash.

In addition, for a first valuation of the process, the Artec Studio software gives the possibility to directly evaluate the quality of the frame registration that composes the individual scans before and after the data processing, although it is recommended to consider the value of the max error only after running the "Global Registration" algorithm. A high value indicates less accurate alignment, consequently, the best results are obtained for lower values in relation to the size of the object we are surveying, and the instrument used. In the case study, the recorded value (max error) averaged 0.2 (which is a good value in the max error ranges for the Artec Spider values).

For the second case study it has become possible to use the photographic output from portable devices with high magnification power at relatively low-cost, the so-called USB digital microscopes, in Structure from Motion methods [31]. They are made up of compact, portable optical zooms that are made for transferring images directly to monitors. The resolution is usually up to 5MP, as the model employed (AM7013MZT by Dino-Lite) has and the sensor size is about 1/4". These USB microscopes, while easy to use, were not created to be tools for image-based three-dimensional reconstructions. This is partly since they do not have the mounts and calibrators needed to make them suitable for photogrammetric applications.

To facilitate and speed up the acquisition process and to appropriately integrate USB digital microscopes into the photogrammetric workflow, the object was placed on a rotating stand (Figure 3). The optical system -placed on a micrometric slide suitable for the radial translation- thanks to its lightweight and small size, can be tilted against the object to be scanned. This is to obtain converging captures always orthogonal to the surface of the object, i.e., the axis of the camera is orthogonal to the plane tangent to the surface of the object in relation to the trace of the axis itself, which is the best condition from a photogrammetric point of view. An adhesive calibrator consisting of a pattern of coded targets was placed at the base of the holder to provide a metric reference in the scene and to define a local coordinate system for model scaling and capture alignment procedure improvement. In this way, there are sets of known coordinate points to be imported as a grid of control points (GCP). Two sets of images, one for the recto and one for the verso of a single earring, consisting of 240 and 257 images, respectively, were acquired with this system. In the Agisoft Metashape software environment, a description is provided for each point in the source photos that remains stable despite changes in viewpoint.

Fig. 3. The image-based acquisition system assembled to employ a USB microscope for photogrammetric purposes.

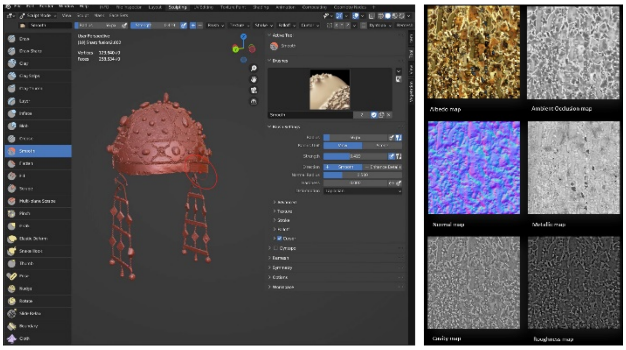

Fig. 4. Digital sculpting techniques for correcting topological errors of the resulting mesh surface.

These descriptions are then used to search for matches between images (features detection) and to determine a rough position for each camera (feature matching). After the tool refinement of those locations using a Self-Calibration Bundle Block Adjustment (structure estimation), the alignment can then be improved (structure optimisation). This stage of the workflow is based on the "Gradual selection filter" and optimization cycles and involves aggressive filtering steps in order to maintain only high-quality Tie Points for the subsequential dense cloud and mesh reconstruction.

V. RESULTS

The geometric-formal complexities of the case studies (polyhedral gemstones, carving and chiselling techniques on very small and elaborate parts) and the type of reflective materials were dealt with acceptably, ensuring in both projects a sufficiently rigorous description of the artefacts.

So, while overall the ambitious attempt to render a complete model of a small and/or complex and detailed object is successful with both technologies, the results obtained must be placed in the context of the purposes for which they should serve. Mainly, both models have topological defects in the generated mesh surface that must be fixed in post-production. Particularly in the case of the "kamelaukion", the main problems were encountered in the phase of texture mapping above all due to the presence of extremely reflective stones, which made it difficult to completely acquire their polygonal geometry. In this case, it was necessary to operate in modelling software Blender to correct topological errors in the resulting mesh surface (Figure 4). This made it possible to share the final three-dimensional model for digital enjoyment of the artefact. Within the interface of Blender software (release 2.8) it was possible to optimize the overall geometry of the model without altering the geometry (mesh collision detection/re-meshing/mesh correction), lightening the polygonal load of the mesh and correcting recurrent topological errors in models derived from 3D scans (double vertices, inverted normal, redundant geometric entities, overlapping edges and faces). Particularly complex was the geometric reconstruction phase in digital sculpting, which involved all those areas of the model that, due to light reflections, had not been returned corresponding to the original, but had incongruent deformations and artifacts (Figure 5).

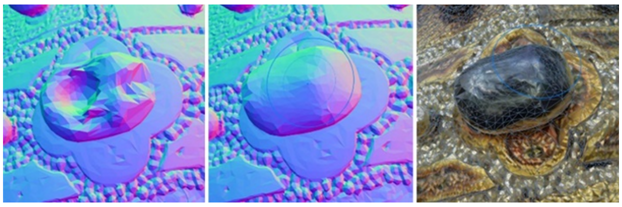

Fig. 5. Reconstruction in digital sculpture of the surface of a gemstone.

Fig. 6. Orthophoto generated with the dataset from the microscopic acquisition (side A).

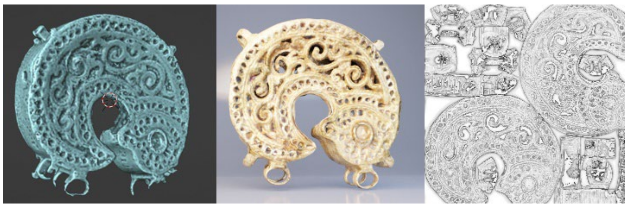

Fig. 7. Readable and virtually manipulable digital replica of one of the so-called earrings "of Constance".

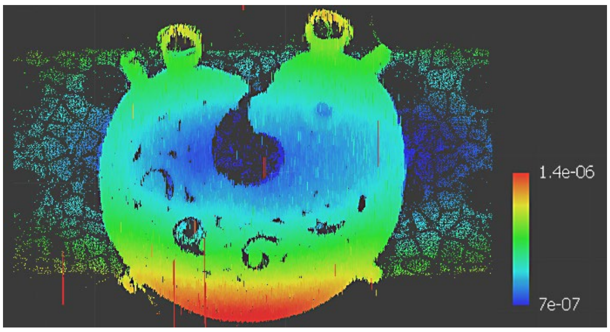

Fig. 8. TPs covariance view mode, after filtering, in Agisoft Metashape software (side B).

The open-source software has an excellent set of tools dedicated to digital sculpting (modifier brushes). Some tools used for gemstone reconstruction are: "clay brush" which adds or removes clay; "smooth" which removes details and smooths the surface; "grab/move" quickly modifies the proportions of a model; "crease" creates indentations or sharp ridges.

In the case of the earrings "of Constance", instead, the main problems were encountered due to the complex geometry of the decorations and for the golden surface characteristics. The ornaments, in fact, inevitably entailed the realisation of a three-dimensional photogrammetric model initially characterised by high noise as well as a lack of three-dimensionality of the internal trelliswork constituting the decorations of the earrings. In addition, because of the few tilted photos – due to the shallow depth of field to manage and the few texture features even along the thickness of the jewel – the reconstruction of the earring's edges had many missing parts.

Therefore, joining the two sides (having acquired the object in two different chunks then joined) to obtain a complete model was very onerous and inaccurate.

However, it is possible to estimate the accuracy of the photogrammetric process beyond the qualitative results that can be visually observed in the initial model, thus changing the purpose of using the output obtained and trying to sculpt and reconstruct the earrings from the rough first results. In fact, it will be admitted that, even if the number of TPs obtained (both upstream and downstream of filtering) did not allow for a sufficiently clean and complete three-dimensional reconstruction, the error associated with them is very low, as shown as follow.

So, in this case, the tool confirms its validity for the purposes of inspection and metric control, but not for the dissemination of the model itself: from the first results it was obtained just a satisfactory detailed orthophoto (7.4 nanometres/pixel) as output for the earrings (Figure 6).

In order to return a 3D model that could be divulged, a digital reconstruction of missing parts as well as re-meshing and re-topology processes were necessary. In addition, the perforated decorative motif was not sufficiently accurate, for this reason, it was decided to improve the texture data, by a dedicated UV vertex map generation pipeline, so that it would give the impression of the holes. In this way, a readable, shareable and virtually manipulable digital replica of this small and delicate find was obtained (Figure 7).

The evaluation of the final SfM model's accuracy is challenging without a reference model since indicators must be derived directly from the photogrammetric procedure.

The simplest analysis to validate the accuracy of the camera alignment could be performed on the Check Points (CPs): 0.1 px reached in our application. However, basing the entire analysis on a limited number of points is not a robust approach. Therefore, the Tie Points (TPs) uncertainties could be studied to perform the direct accuracy assessment of the photogrammetric model. By estimating the TPs covariance matrix, which is connected to the execution of the Bundle Block Adjustment, the uncertainty in the camera models may be shown: selecting a particular TPs cloud display mode, the evaluation results can be viewed (Figure 8).

This description shows in false colours for each TPs associated vector – which has three components that are the semiaxes of the error ellipsoid with k = 1 specified by the covariance matrix – the direction and magnitude of the error for the TPs estimated position [32]. Thus, an estimate of the maximum error on the previously filtered TPs (high quality TPs only) of 1.4 micrometres is allowed.

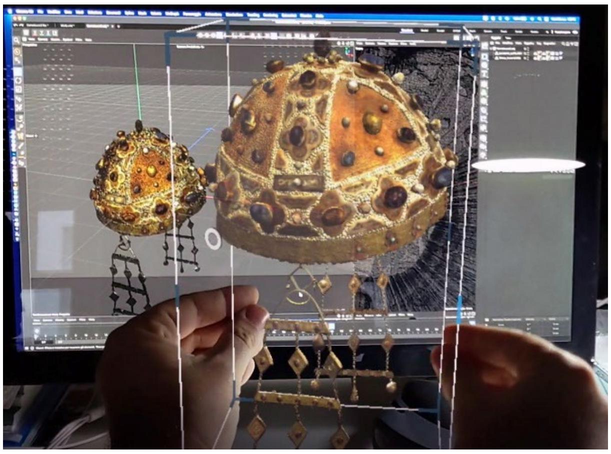

Fig. 9. Interaction of the three-dimensional model through the hologram system (Microsoft Hololens 2).

Fig. 10. Holographic device for the fruition of the digital model of the "kamelaukion" (Oloproject's Olobox device).

The study also presents some results related to the experimentation of innovative virtual visualisation solutions in mixed reality (holographic visualisation with Hololens 2_Microsoft devices and with specially designed desktop devices, Oloproject's Olobox) to disseminate the results and fruition of the models developed (Figures 9-10). With current 3D viewers (Oculus), manipulation of 3D objects other than vision is not allowed.

Manipulation (turning the object, changing its size) is allowed by augmented and mixed reality viewers. Regarding Microsoft Hololens 2 Viewers, we studied the behaviour of the viewer with the 3D model of the Constance of Aragon's "kamaleukion", in internal and external spaces, with natural light, artificial light and mixed light.

HoloLens system has the problem of working online, so the three-dimensional model must have a low number of polygons, different from the one needed with Oculus (which can work offline). About HoloLens, it is therefore necessary to favour the texture, and lower the number of polygons of the 3D object (.LGB format). About the use of the holographic device Holobox with a pyramidal structure with three projection faces, a video (Full HD 1920x1080 px 25p or 50p video resolution, .mp4 format) with the following design features had to be made: black background; a single video divided into three parts (three projections of the same model; mirrored effect; objects/Animations distant from the edges.

VI. CONCLUSIONS

The survey carried out with different instruments proved to be appropriate for the characteristics of the study objects. However, there were some difficulties during the restitution process. This demonstrates the complexity of the surveying operations that are encountered for each case study and that must be considered for each object, especially when working with assets of historical and cultural value such as artefacts preserved in museums.

The work conducted allowed us to experiment with different technologies, highlighting their peculiarities but also the limits that each of them has in particularly complex conditions. Like often happens in the archaeological environment, the objects to be surveyed present unique as well as varied characteristics, which is why a single type of instrument is often not always able to completely render the final three-dimensional model.

Despite the difficulties encountered, however, this work underlines the potential of new digital tools for the dissemination and enjoyment of archaeological heritage.

Examples of this are the exhibits through holograms created with the objects presented here. The acquisitions, in fact, have allowed the fruition of a heritage that to date was not accessible to the public, making its knowledge and dissemination possible. The process of disclosure was only possible following the editing of the data in Blender, in fact, to make the model more manageable it was necessary to proceed to a decimation of the mesh without, however, compromising the final quality of the geometry and texture.

The study aims to develop critical reflections on the value (limits and potential) of experimental methodological processes applied to the documentation and knowledge of cultural heritage, using the integrated digital technologies available today, for 3D digital survey and representation. In the future, it is hoped to further investigate the characteristics of the instruments used, possibly comparing them with new ones, as well as hypothesising their integration.

CREDITS

Authors' contributions: all authors conceived and designed the survey campaign; they examined the data, verified the methods and discussed the results. F.D.P. wrote "Introduction" and "Conclusions"; S.A. and S.M. wrote "State of the Art" and "Complex Surfaces"; S.A., S.M. and F.D.P. wrote "Materials and Methods", in particularly S.M. and F.D.P. investigated the parts related to structured light scanner and S.A. to photogrammetry; S.A., S.M. and G.R. performed and wrote "Results".

ACKNOWLEDGEMENT

The Authors thank Sicily Regional Gallery, Palazzo Abatellis, Director, Drs. Maddalena De Luca and restorers Drss. A. Bombace, A. Leto, B. Pastena. The Authors thank, also, to Rev.do Mons. Filippo Sarullo, Parish priest of the Cathedral of Palermo. In addition, the authors thank Dr. Yuri Alogna for participating in some processing of the final models.

DISCLAIMER

The VR/AR contents, the Holograms and the publication itself have been produced with the financial assistance of the European Union under the ENI CBC Mediterranean Sea Basin Programme. The contents of this document are the sole responsibility of the project staff and can under no circumstances be regarded as reflecting the position of the European Union or the Programme management structures. iHERITAGE. ICT Mediterranean Platform for UNESCO Cultural Heritage (https://www.unipa.it/dipartimenti/architettura/iHERITAGE/index.html) is a project financed by ENI CBC MED Program 2014-2020, UNIPA scientific Head Prof. Rossella Corrao (https://www.enicbcmed.eu/projects/iheritage).

REFERENCES

[1] F.I.Apollonio, F.Fantini, S.Garagnani, M.A.Gaiani, "A Photogrammetry-Based Workflow for the Accurate 3D Construction and Visualization of Museums Assets". Remote Sensing 2021, 13, 486-515.

[2] M.Accascina, "Oreficeria di Sicilia dal XII al XIX secolo", 1974.

[3] M.Accascina, "L'ordinamento delle oreficerie del Museo Nazionale di Palermo", BArte, s. II, 9, 1929, pp. 225-231.

[4] M.C.Di Natale, "Un Paio di orecchini d'oro in filigrana", Constancia. Donne e potere nell'impero mediterraneo di Federico II, p.122.

[5] Piano Nazionale di Ripresa e Resilienza #nextgenerationitalia: www.governo.it/ sites/ governo.it /files/PNRR_0.pdf

[6] M.L.Galantucci, M.G.Guerra, F.Lavecchia, "Photogrammetry Applied to Small and Micro Scaled Objects: A Review", Proceedings of 3rd International Conference on the Industry 4.0 Model for Advanced Manufacturing, Ni, J., Majstorovic, V., Djurdjanovic, D. (eds); Lecture Notes in Mechanical Engineering. Springer, Cham, 2018.

[7] T.Luhmann, S.Robson , S.Kyle, J.Boehm, "Close-Range Photogrammetry and 3D Imaging", De Gruyter, 2020.

[8] D.Ding, W. Ding, R.Huang, Y. Fu, F. Xu, "Research progress of laser triangulation on-machine measurement technology for complex surface: A review", Measurement, Vol. 216, 2023.

[9] B.Cui, W.Tao, H.Zhao, "High-Precision 3D Reconstruction for Small-to-Medium-Sized Objects Utilizing Line-Structured Light Scanning: A Review", Remote Sensing. 2021, 13(21):4457.

[10] S.Zhang, "High-speed 3D shape measurement with structured light methods: A review", Optics and Lasers in Engineering 2018, Vol. 106, 119-131.

[11] J.G.Webster, T.Bell, B.Li, S.Zhang, "Structured Light Techniques and Applications". In J.G.Webster (Ed.). Wiley Encyclopedia of Electrical and Electronics Engineering 2016, 1-24.

[12] P.Ghandali, F.Khameneifar, J.R.R.Mayer, "A pseudo-3D ball lattice artifact and method for evaluating the metrological performance of structured-light 3D scanners", Optics and Lasers in Engineering 2019, Vol. 121, 87-95.

[13] S.Morena, S.Barba, A.Álvaro-Tordesillas, "Shining 3D Einscan-pro, application and validation in the field of cultural heritage, from the Chillida-Leku museum to the archaeological museum of Sarno", The International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences 2019, XLII-2/W18, 135–142.

[14] F.Diara, "Structured-Light Scanning and Metrological Analysis for Archaeology: Quality Assessment of Artec 3D Solutions for Cuneiform Tablets", Heritage 2023, 6, 6016-6034.

[15] J.Moyano, E.Cabrera-Revuelta, J.E.Nieto-Julián, M.Fernández-Alconchel, P.Fernández-Valderrama. "Evaluation of Geometric Data Registration of Small Objects from Non-Invasive Techniques: Applicability to the HBIM Field". Sensors 2023, 23, 1730.

[16] L.Inzerillo, F.Di Paola, Y.Alogna, "High quality texture mapping process aimed at the optimization of 3D structured light models". The International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences 2019, XLII-2/W9, 389-396.

[17] M.E. Polo, Á.M.Felicísimo, G.Durán-Domínguez, "Accurate 3D models in both geometry and texture: An archaeological application", Digital Applications in Archaeology and Cultural Heritage 2022, Vol. 27, 1-9.

[18] A.Gallo, M.Muzzupappa, F.Bruno, "3D reconstruction of small sized objects from a sequence of multi-focused images", Journal of Cultural Heritage 2014, 15(2), 173-182.

[19] H.N.Hansen., K.Carneiro, H.Haitjemac, L.De Chiffrea, "Dimensional Micro and Nano Metrology", CIRP Annals 2006, 55(2), 721-743.

[20] T.Collins, S.I.Woolley, E.Gehlken, E.Ch'ng, "Automated Low-Cost Photogrammetric Acquisition of 3D Models from Small Form-Factor Artefacts", Electronics 2019, 8, 1441-1458.

[21] M.C.Arriaza, J.Yravedra, M.Domínguez-Rodrigo, M.Ángel Mate-González, E.G.Vargas, J.F.Palomeque-González, Aramendi J., D.González-Aguilera, E.Baquedano, "Applications of Micro-Photogrammetry and Geometric Morphometrics to Studies of Tooth Mark Morphology: The Modern Olduvai Carnivore Site (Tanzania)", Palaeogeography, Palaeoclimatology, Palaeoecology 2017, 488, 103-112.

[22] F.Menna, E.Nocerino, D.Morabito, E.M.Farella, M.Perini, F.Remondino, "An open source low-cost automatic system for image-based 3D digitization", The International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences 2017, XLII-2/W8, 155-162.

[23] F.Dai, Y.Feng, R.Hough, "Photogrammetric error sources and impacts on modeling and surveying in construction engineering applications", Visualization in Engineering 2014, 2(2), 1-14.

[24] D.Gajski, A.Solter, M.Gašparović, "Application of macro photogrammetry in archaeology. The International Archives of the Photogrammetry" Remote Sensing and Spatial Information Sciences 2016, XLI-B5, 263-266.

[25] M.Rodríguez-Martín, P.Rodríguez-Gonzálvez, "Suitability of Automatic Photogrammetric Reconstruction Configurations for Small Archaeological Remains", Sensors 2020, 20, 2936-2955.

[26] D.Gajski, A.Solter, M.Gašparovic, "Applications of macro photogrammetry in archaeology", The International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences 2016, XLI-B5, 263–266.

[27] C.Nicolae, E.Nocerino, F.Menna, F.Remondino, "Photogrammetry applied to problematic artefacts", The International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences, 40, 451-456.

[28] S.Marziali, G.Dioniso, "Photogrammetry and Macro Photography. The Experience of the MUSINT II Project in the 3D Digitization of Small Archaeological Artifacts", SDH 2017,1, 2, 298-309.

[29] M.E.Marshall, A.A.Johnson, A. A., S.J.Summerskill, Q.Baird, E.Esteban, "Automating photogrammetry for the 3D digitisation of small artefact collections", The International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences 2019, XLII-2/W15, 751–757.

[30] M.Schaich, "Combined 3D scanning and photogrammetry surveys with 3D database support for archaeology & cultural heritage. A practice report on ArcTron's information system aSPECT3D", Proceedings of Photogrammetric Week 2013, D. Fritsch (ed.); Wichmann, Berlin/Offenbach, 2013.

[31] F.Esmaeili, H.Ebadi, "Handy Microscopic Close-Range Videogrammetry", The International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences 2017, XLII-4, 65-67.

[32] A.diFilippo, S.Antinozzi, A.Dell'Amico, A.Sanseverino, "A statistical analysis for the assessment of close-range photogrammetry geometrical features", The International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences 2022, XLVIII-2/W2, 31-38.