Digital Applications in Archaeology and Cultural Heritage 20 (2021) e00179

Contents lists available at ScienceDirect

Digital Applications in Archaeology and Cultural Heritage

journal homepage: www.elsevier.com/locate/daach

Digital 3D modeling using photogrammetry and 3D printing applied to the restoration of a Hispano-Roman architectural ornament

María Higueras *, Ana Isabel Calero, Francisco José Collado-Montero

Department of Painting, Faculty of Fine Arts, University of Granada, Avenida de Andalucía, s/n, 18071, Granada, Spain

ARTICLE INFO

Keywords:
Non-invasive restoration
Photogrammetry
3D printing
Reintegration
Archaeology
3D modeling

ABSTRACT

New technologies provide the means to record images of cultural assets and, subsequently, process them to obtain virtual or physical items, guaranteeing greater respect for their physical integrity.

The main purpose of this paper is to demonstrate a useful workflow concerning photogrammetric techniques, specific software and 3D printing for the application of non-invasive restoration treatments.

The applied methodology was based on the application of photogrammetric digital 3D modeling to obtain virtual models of a Roman cornice from *Castulo* Archaeological Site (located in Spain), along with the subsequent use of those models for the material restoration of the losses, by making the 3D printing of the piece for the reintegration.

The results demonstrate that the losses can be accurately and controllably filled in by direct reintegration, potentially in several 3D printing materials, and by using a mold, which could also be printed. The automatic creation of the mold using specific software could considerably reduce the manufacture process.

1. Introduction

Thanks to the rapid progress in the application of new technologies in multiple fields, those techniques for the digital record of reality, such as photogrammetry or 3D scanning, have been effectively established in the field of cultural heritage. There is not only new and improved equipment offering advantages such as easy transport, speed and improvement of its applications, but also many programs enabling the obtention of maximum benefits when using this equipment with a minimum investment of resources.

Within the techniques for the 3D digital record of reality accessible nowadays, photogrammetry and 3D scanning are the ones which stand out. Each of them has its own advantages and disadvantages, thus the choice between them depends on the type of project, the objective of the digitalization process and the results which are expected to be achieved (Delpiano et al., 2017; Díaz Martínez et al., 2018; Dulieu-Barton et al., 2005; Erolin et al., 2017).

When compared with the recording techniques which have traditionally been used in the field of heritage (such as life drawing, sketches and simple photographs from different points of view), and archaeology in particular, photogrammetry has shown its capacity to provide 3D virtual models on the basis of two-dimensional recordings, even from stock or ancient photographs. Therefore, the cost and the time needed for documentation are reduced, whereas the amount of information obtained is considerably increased (Davis et al., 2017; Foramitti, 1980; Resco et al., 2014). For example, photogrammetry can be included in the workflow of archaeological diggings, generating virtual products with information of great interest about the materials of archaeological origin (De Reu et al., 2014; Jaklič et al., 2015; Maté González et al., 2015; Zangrossi et al., 2019).

Photogrammetry also provides a few advantages if compared to other recording techniques. One of these advantages is the possibility of recording any object that is accessible to photography, irrespectively of its dimensions and shape, assessing its material qualities to plan the most effective methodology for digitalization (McCarthy, 2014). In this respect, Pérez-García et al. (2019) have proven the effectiveness of photogrammetric recording in difficult-to-access spaces within archaeological sites. In addition, Waagen (2019) proposes to follow a photogrammetric methodology in the recording of archaeological sites using Unmanned Aerial Systems (UAS). On the other hand, Rivero et al. (2019) carried out the recording of Paleolithic thin incised engravings by means of close-range photogrammetry.

As a disadvantage, the photogrammetric process can be slow, since the dimensions of the piece and the desired level of definition determine

* Corresponding author.
E-mail addresses: mariahimu@correo.ugr.es (M. Higueras), anacalero@ugr.es (A.I. Calero), fcollado@ugr.es (F.J. Collado-Montero).

https://doi.org/10.1016/j.daach.2021.e00179
Received 30 September 2020; Received in revised form 6 February 2021; Accepted 20 February 2021

the higher or lower number of photographs that must be systematically taken. Likewise, certain materials with characteristics of transparency or light reflection are difficult to record with photogrammetric techniques.

From a financial point of view, photogrammetry stands as a relatively affordable method considering that the equipment needed is usually composed of, basically, a computer with a high capacity for data processing and a digital camera (Evin et al., 2016).

There are different types of software for the digital treatment of the information obtained. They can be classified, based on their purpose, in applications for the treatment, representation (generation of 3D models), modeling and 3D treatment of images. Some of the most recommended programs are *Agisoft Metashape* (photogrammetric mapping), *AutoDesk* (CAD), *Meshlab* (modeling and 3D treatment), *Visual SFM* (photogrammetric survey), *iWitness Pro* (photogrammetric mapping) and *Blender* (modeling and 3D treatment), among others (Davis et al., 2017). It is important to highlight that certain programs are free and open-source software, consequently reducing costs and improving the efficiency of those resources allocated to the digitalization process.

The obtention of 3D virtual models with metric accuracy in relation to the original measurements has diverse applications in the field of cultural heritage. These applications range from the documentation, research and promotion of cultural heritage to its reconstruction, virtual reintegration and 3D printing for its reproduction and physical reintegration (de la Torre Cantero, 2015; Fioretti et al., 2020; Rodríguez Hidalgo, 2010; Vranich, 2018). It is noteworthy that they are also used in the field of restoration as a tool to assess the interventions carried out (López-Martínez et al., 2018; Palma et al., 2019; Torres et al., 2010).

On the one hand, the processing of virtual models with different software programs allows the virtual reintegration and reproduction of cultural heritage (Arbace et al., 2013; Blitz, 2019; Davis et al., 2017; Huang et al., 2006). The spectator has a digital model available which faithfully and accurately reproduces the original, with the possibility of displaying the complete object in 3D, by means of a screen or even with mixed reality systems (Brown et al., 2012; Echavarria et al., 2020; Palmas et al., 2013). Therefore, the legibility of the cultural asset is recovered and it can be interactively observed from all possible views (Arbace et al., 2013; Bernardi et al., 2019; Koutsoudis et al., 2014; Petrelli, 2019; Rahaman et al., 2019).

On the other hand, creating virtual models and reproducing them physically via 3D printing provides a real object useful for teaching and museographic purposes; an object which can be used by all kind of visitors, including those suffering from visual impairment (tiphlological reproductions) (Balletti et al., 2017; Evin et al., 2016; Wilson et al., 2018).

3D printing technologies have been recently introduced in the cultural heritage field, showing a large variety of applications. It should be highlighted in the scope of action of 3D printing the physical reintegration of lacunae in cultural heritage. For this, the appropriate methodology would involve the direct physical 3D printing of the virtual reintegration or the reproduction of a virtual mold (Alderighi et al., 2018, 2019; Herholz et al., 2015; Malomo et al., 2016).

This paper proposes to create the 3D model of the losses and subsequently reproducing them by means of 3D printing or direct printing from a mold (from which the missing element can be obtained, using moldable materials compatible with the original) (Díaz-Marín and Aura-Castro, 2017; Hernández-Muñoz and Sánchez-Ortiz, 2019). Both techniques aim at operating with non-invasive methods that considerably reduce the need of handling the original artefact and the risk to the object during the intervention for its reintegration, as well as using more sustainable techniques thanks to the use of recyclable and/or biodegradable printing materials.

This way, the main contribution of this paper is focused on the proposed workflow and methodology, from the discovery of the archaeological artefact to its physical reintegration. This methodology includes the use of a novel tool (currently under development in the Ultimaker Cura software) for the automatic creation of a mold, which could considerably reduce the manufacture process. Another contribution concerning the execution technique of the cornices is the verification of the execution technique itself through the inspection of the original cornice and the digital model generated. Also, the design of typological models of the original cornices contribute to the research study of this sort of cultural assets worldwide. This is postulated as a great opportunity to compare and explore different possibilities of ornamental trends, displacement of the artists or the trading of molds.

2. Materials and methods

The materials and methods used in this research to accomplish the objective can be summarized as follows: 2.1. Selection of an embossed fragment of archaeological origin; 2.2. Material characterization of the fragment; 2.3. Photogrammetric mapping of the piece with *Agisoft Metashape*; 2.4. Virtual reintegration with *Blender* and *3D Builder*; 2.5. Digital modeling of the mold for the reintegration; 2.6. Digital modeling of the typological model; 2.7. 3D printing of the reintegration and the typological model.

2.1. Selection of an embossed archaeological fragment

The city of *Castulo*, a distinguished settlement in the Iberian Oretania, became a prosperous Roman city, as shown by the preserved constructions from that period (baths, temples, mosaics and sculptures of high quality). It was abandoned due to a declined period characterized by a lack of available resources, especially the mining ones. Because of this abandonment, numerous archaeological assets have been preserved. The city was declared Archaeological Site in 2011. As a result, several excavation campaigns were carried out, revealing spaces such as the *Sala del Mosaico de los Amores* or the Christ in Majesty paten (López-Martínez, 2015; López Rodríguez et al., 2017; Salvador and Muñoz, 2019).

Among all the discoveries in this archaeological site, the preservation state of the embossed wall covering is to be emphasized. The importance of these types of pieces lies in their exceptional nature, as Roman cornices (embossed frames which finish off the upper part of the walls) have hardly ever been preserved in archaeological sites, since they were located in the upper part of the walls and they tended to detach so, consequently, very few references exist in this respect. From the beginning of this research, we could corroborate the lack of documentation on this typology of materials, highlighting a few publications by Guiral-Pelegrín, Íñiguez and Martín-Bueno, that focus on the Archaeological Site of *Bilbilis*, in the province of Zaragoza (Guiral Pelegrín et al., 2017, 2019; Guiral Pelegrín and Martín-Bueno, 1996); as well as other studies carried out in the Italian peninsula (Cagnana and Mannoni, 2000; Famiglietti and Scioscia-Santoro, 2001).

One of the main objectives of this research is applying the proposed methodology to a unique embossed piece whose volumetric reintegration is to be of interest for fragments of similar typologies. To do so, the fragment was chosen from cornice 1B.EST.6, a fragment that had been discovered during the excavation campaigns of *Castulo* Archaeological Site (Linares, province of Jaén). This piece comes from room number six, marked in the planimetry. This room has a very rich wall decoration, and figurative ornaments showing different roman deities. The upper part of the cornice is composed of a floral garland where no remains of color have been preserved. However, the part of the cornice in contact with the vertical wall is painted in a perfectly preserved blue color (Fig. 1).

Roman cornices used to be produced before the final painting of the wall. Once the wall coating was completed and before spreading the last covering of mortar, the cornice was usually placed using a diestock, a wooden mold or direct sculpting. The diestock or the mold were used for the reproduction of modest ornaments while the sculpting with chisels was reserved for more complex patterns (Guiral Pelegrín, 2000; Mostalac Carrillo and Guiral Pelegrín, 1994).

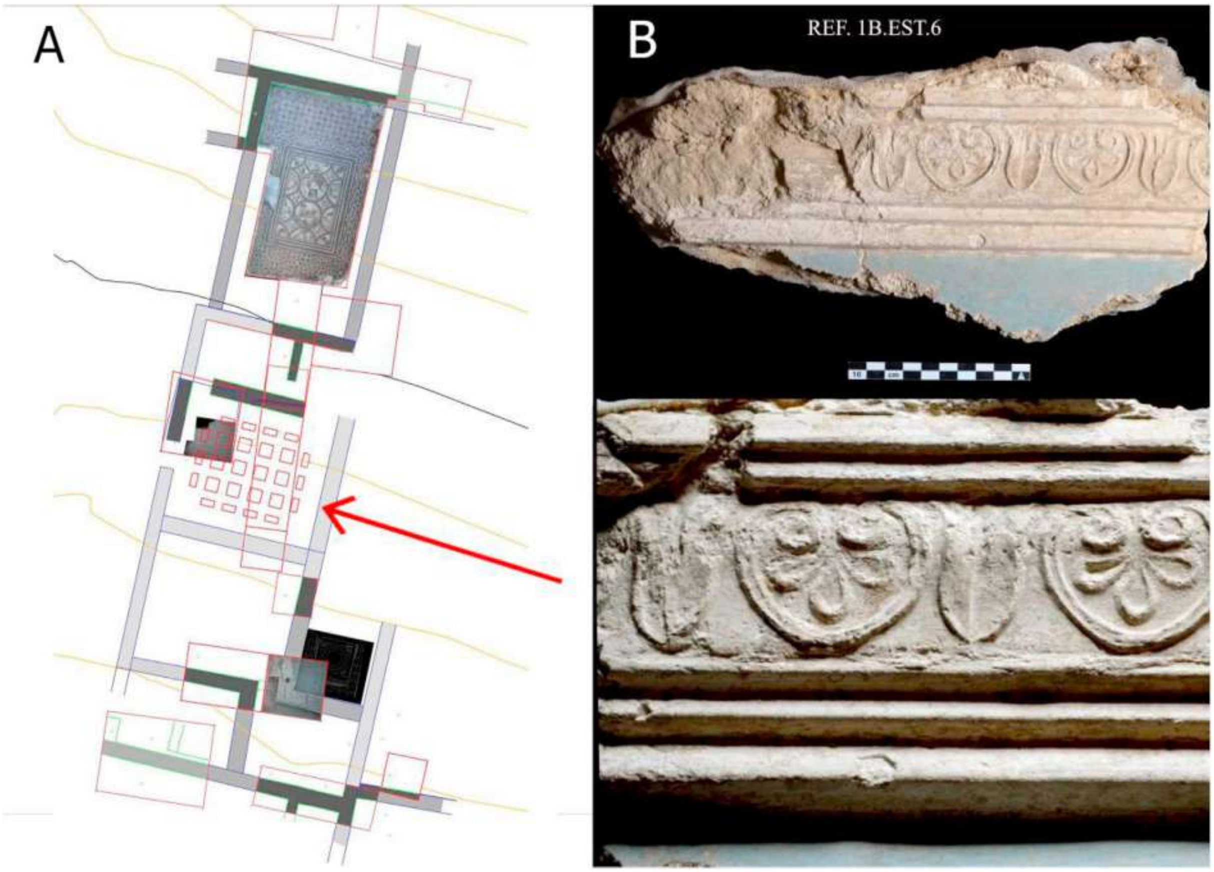

Fig. 1. A) Aerial planimetry of the archaeological site provided by the FORUM MMX team; B) General image and detail of the studied fragment.

2.2. Material characterization of the fragment

Characterizing the fragment was aimed at obtaining information on the execution materials and techniques.

In order to determine the material composition and the main components of the polychrome wall covering (mortars and pigments), we carried out a representative sampling for analysis. For this purpose, a total of six samples were collected with a scalpel and placed in referenced inert containers. Two of them were used for the X-ray diffraction study and another two to identify the components of the pictorial layer with thin sections (Almaviva et al., 2019; Taglieri et al., 2019; Tortora et al., 2016).

2.2.1. Analysis techniques

2.2.1.1. Stereoscopic microscopy. This analysis provided global information on the sample, enabling the identification of the different layers and providing a first approach to the textural characteristics. This test requires a minimal quantity of sample and requires no preparation of it. We used a NIKON SMZ 1000 microscope with parallel optical beam fit for photomicrography. This microscope was equipped with infinity-corrected optical systems and its zoom factor ranged from 0.8x to 8x,

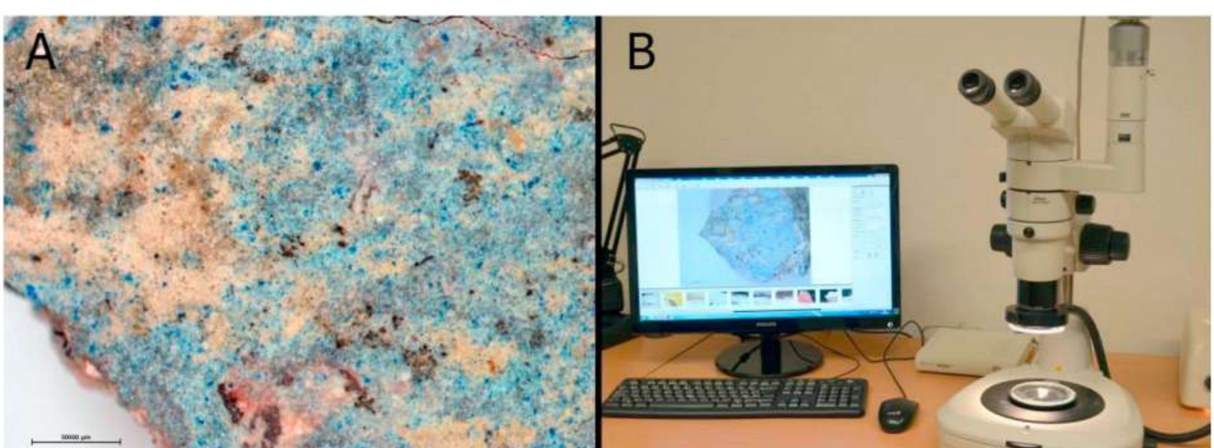

Fig. 2. A) Detailed image of the blue sample surface; B) Analysis of the sample with stereoscopic microscope. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

offering magnifications from 4x to 480 (Fig. 2).

2.2.1.2. Petrographic microscopy. Analyzing samples using polarized light can be a very useful supplementary technique to differentiate the nature of those layers or materials. This technique requires the preparation of samples in polished-thin sections from their transverse sections. The Carl Zeiss-Jena Jenalab and the Olympus BX-0 microscopes were used, the latter equipped with a DP-20 photomicrography system; and both equipped with polarizer and cross polarizers.

2.2.1.3. Scanning electron microscopy (SEM/EDX). This technique allowed the identification of the surface structure of the sample, its transverse section, the morphology of its grains and crystals and the elemental composition of specific areas by analyzing the X-ray spectra obtained. In this case, the thin sections were metallized with a thin carbon layer. The equipment used consisted of a scanning electron microscope HITACHI S-510 with 25kv accelerating voltage offering magnifications ranging from 20x to 150.000x at 5 mm working distance, SE detector (7 nm–25kv resolution), BSE detector, EDX detector 8 and Edwin microanalysis system by Röntec.

2.2.1.4. X-ray diffraction (XRD). This kind of analysis was key to determine and quantify the crystalline mineral phases of the mortars. The samples were grinded in agate mortar for the obtention of very fine powder which was then introduced in the aluminum sample-holder of the diffractometer. The analyzes were carried out ranging from 4400 cm to 1 and 370 cm-1, with KBr pellet technique or with superficial analysis with UATR technique (Universal Attenuated Total Reflectance). We used a BRUKER D8 ADVANCE powder diffractometer with Cu radiation (sealed tube) and LINXEYE detector. XPOWDER software (2018.01.10. version) was used to analyze the results obtained.

2.3. Photogrammetric mapping

For the photogrammetric mapping of the Roman cornice, we followed a methodology of static positioning of the photographic camera, as the dimensions of the piece made it possible to use this technique. This methodology involves the movement of the artefact, facilitating the control of the overlapping of the photographs. The object was placed on a rotatory platform and the photographic shooting was conducted with approximately 10° turn making sure that enough overlapping (at least 70%) between images was being respected. It is essential to underline the importance of placing a uniformly colored background, in this case black, contrasting with the general tonality of the piece, in order to facilitate the automatic arrangement of the masks.

The equipment used for the photographic record was a Nikon camera body, model D7000, with 50 mm fixed focal length lenses (adapted to the dimensions of the fragment. This focal length provides more accuracy in the texture and less distortion in the image); a light box, where the platform and the fragment were placed to obtain diffuse light when placing the spotlights outside; a tripod for the camera suitable for height regulation; a rotary platform marked in one point to take the photographs; and a MSI computer model GS63 Stealth 8RD.

The photographic parameters were set in manual mode with ISO 100, f/11 and 0.77s shutter speed. This diaphragm setting was chosen to guarantee the focus of the entire object and the shutter speed also depended on the ambient light (for information see Long, 2019). The manual focus was carried out on the surface of the object and the white balance was left automatic, as we used a color chart (ColorChecker Passport by X-Rite) as reference to manage color in the photographs,

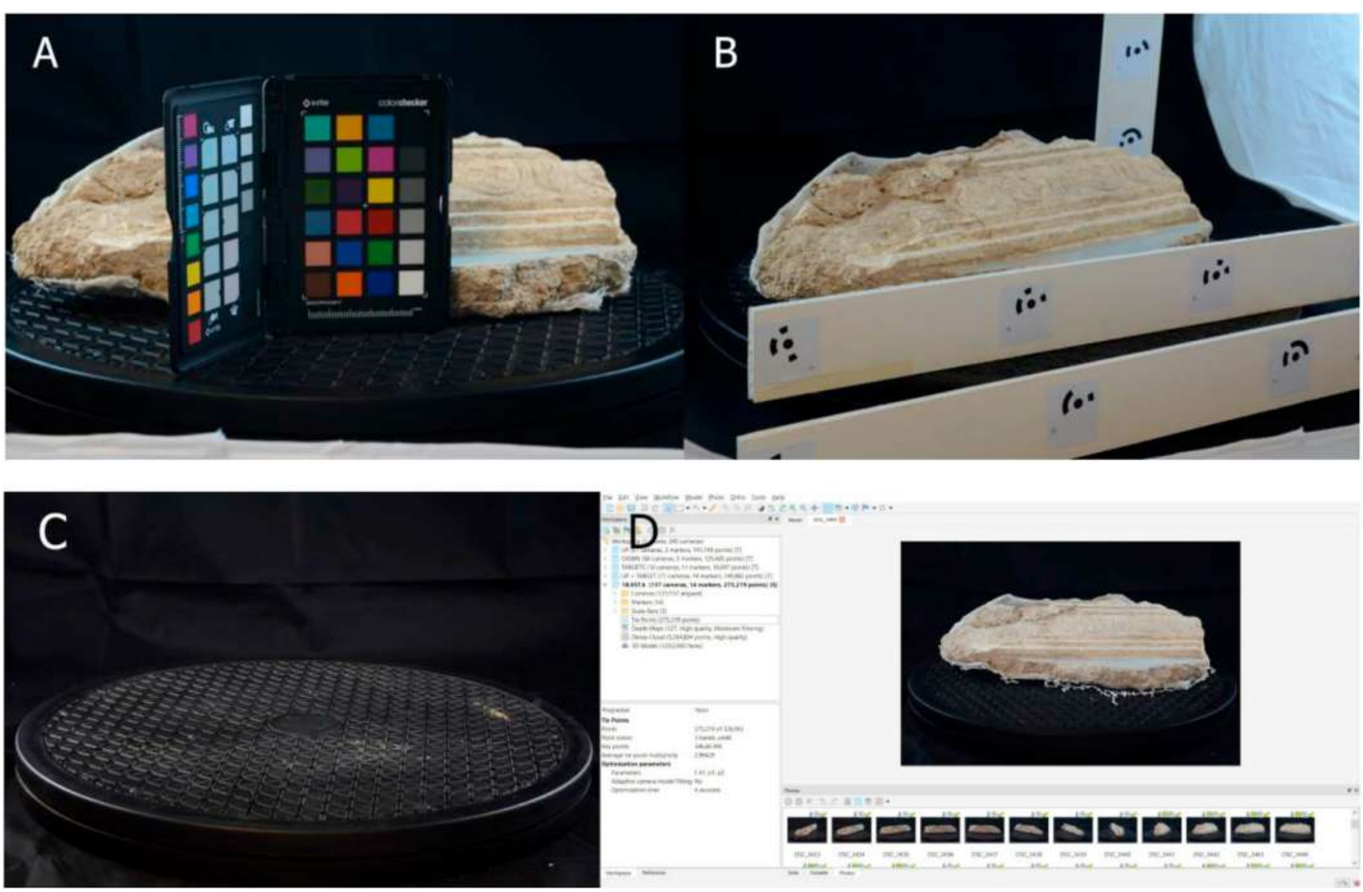

Fig. 3. A) Color chart photograph; B) Positioning of the target points; C) Photograph of the background to import the masks; D) Automatic positioning of masks from the background. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

following the recommendations of Pereira Uzal (2013) (Fig. 3).

As the object is a free-standing fragment, each of its views could be fully documented. In order to do so, we took photographs of the fragment obverse and reverse, and they were processed as two independent blocks in *Agisoft Metashape* software (professional edition, 1.5.2.7838 version). Some target points, automatically generated with the same software, were printed and placed around the object to later unify both blocks and subsequently size them (Fig. 3).

First, we took a photograph of the background without the object and, using the software and before orienting the images, the masks were imported to the background of each photograph. The arrangement of the masks can be made either manually or importing them from the background picture which had already been taken (Fig. 3). This second option is quicker and equally effective, reducing data processing time to a large extent. As we used a neutral color in the background, only one photograph was needed to import the masks.

Then, we generated dense point clouds and meshes of the fragment, following the steps available in the workflow menu of the software. Finally, the 3D models were exported to OBJ format, including the texture from the photographs.

2.4. Virtual reintegration of lacunae

The virtual model of the reintegration was made using *Blender* (2.79 version) and *3D Builder* (18.0.1931.0 version) software. They were chosen for two reasons: first of all, they are freeware and, in the case of *Blender*, it is also open-source software; secondly, they constitute an accessible methodology, as their simple and intuitive interfaces are easy to work with even with little previous knowledge on virtual modeling software.

First of all, and using *Blender*, the photogrammetric mesh of the fragment (hereinafter Cast) was imported and duplicated (hereinafter Cast*) with the objective of modeling the reintegration on the basis of an object with a surface equal to that of the original piece (Fig. 4). Likewise, a metric scale in millimeters was established to work with the model and to subsequently export the scaled model.

To create the model of the reintegration, we worked on multiple Cast* models, repeating a process of duplicating and cutting the model using a simple object (Cube) and applying Boolean-type modifiers to cut the appropriate regions (Fig. 4).

After that, all cut models were virtually aligned with respect to the original model Cast to ensure the orientation and continuity of the cornice geometry. The final model (hereinafter Cast2), which constitutes

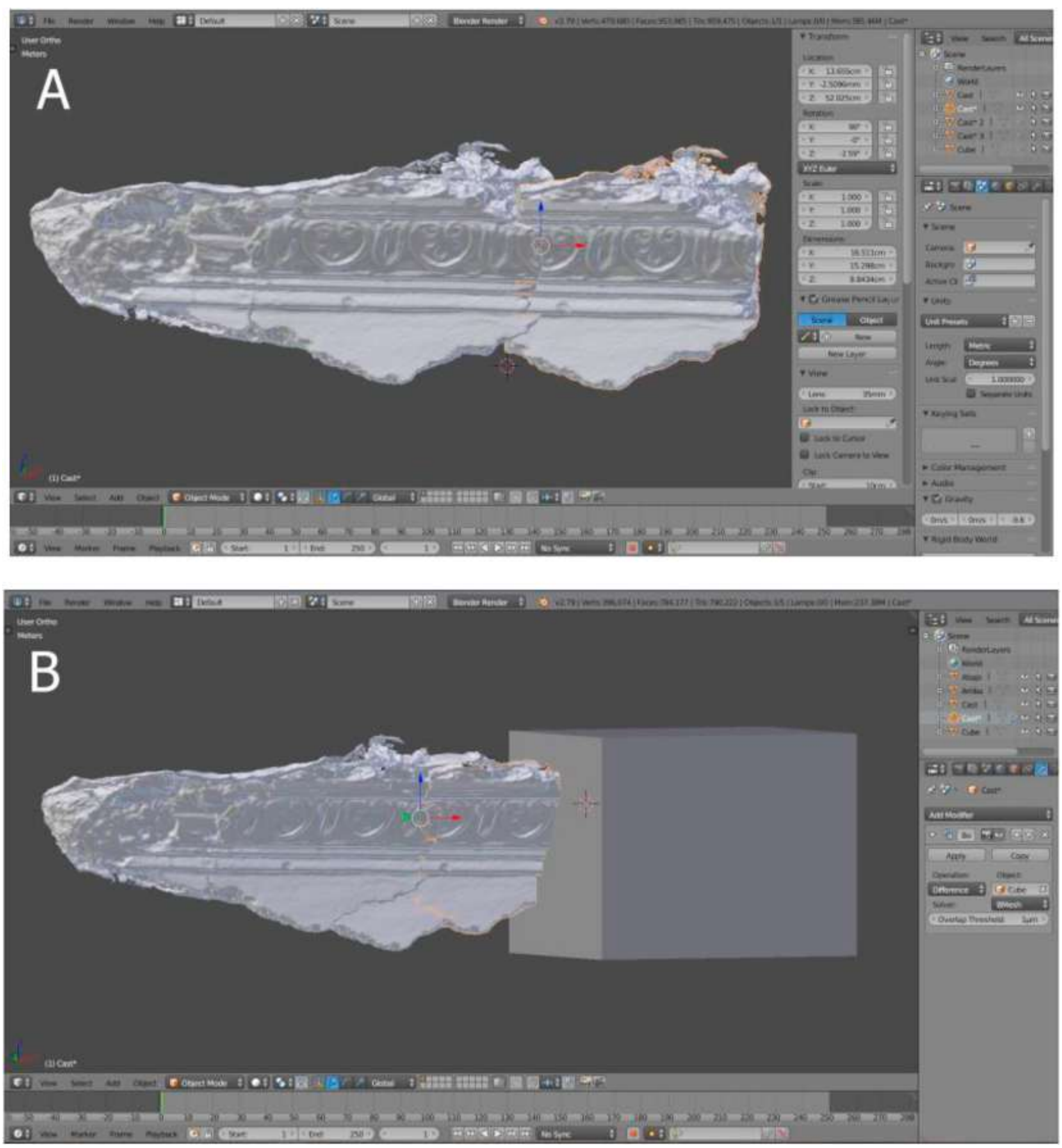

Fig. 4. A) Duplicate of Cast model; B) Cut made using Boolean modifiers.

the complete reintegration, is composed of the sum of the previously cut Cast* models. The Cast2 reintegration was exported to STL format on the appropriate scale.

The next step was importing Cast2 model into *3D Builder* software. The interface of this program is quite simple to use, and it was chosen because it is easy to adjust the virtual reintegration to the Cast photogrammetric model. Upon selection of the metric scale, the software automatically offers the possibility of repairing the imported 3D model if a failure in the polygonal mesh is found. In this study, the software was also used to merge the different slices of the model, deleting those vertexes and polygons remaining inside the virtual model, since they could later interfere with the 3D printing.

Afterwards, the original model Cast was imported with the same scale and was aligned with the Cast2 mesh. The "Subtract" tool was used to delete the difference in volume of the model Cast with respect to the reintegration, so that both geometries would fit together (Fig. 5).

Finally, the Cast2 model adapted with *3D Builder* was exported to STL format and processed again using *Blender* to model some shapes and details of the reintegration using the "Sculpting" mode (Fig. 5).

2.5. Digital modeling of the mold for the reintegration

Apart from virtually reintegrating the lacuna, we also generated a digital mold of the Cast2 reintegration with two alternative procedures. On the one hand, the "mold" tool available in the special modes of *Ultimaker Cura* software (4.3.0 version) automatically generates a covering for the object which is to be printed (Fig. 6). On the other hand, we used Blender to create a bivalve mold from Cast2 model, a cube and spheres to generate shape keys in the mold (Fig. 6).

2.6. Digital modeling of the typological model

With the objective of creating a piece that could be used for the study and promotion of the different decorative typologies of Roman cornices, we created an idealized digital model reproducing the ornamentation of the studied cornice (Fig. 7). In this way, we created an interesting resource for its historical-scientific study and its promotion.

The starting point for the creation of this typological model was the original photogrammetric fragment Cast, whose geometry was duplicated to obtain a continuity of the decorative motifs. After this, the model was sliced with Boolean modifiers on each of the sides using a simple geometry (cube). Finally, some of the volumes were retouched with digital sculpting tools.

2.7. 3D printing of the reintegration and the typological model

The final model of the reintegration was printed in 3D to ensure that it fit the original material, confirming the potential of three-dimensional printing in the field of the restoration of cultural heritage, in this case, cornices. This was made using a Fused Deposition Modeling (FDM) 3D

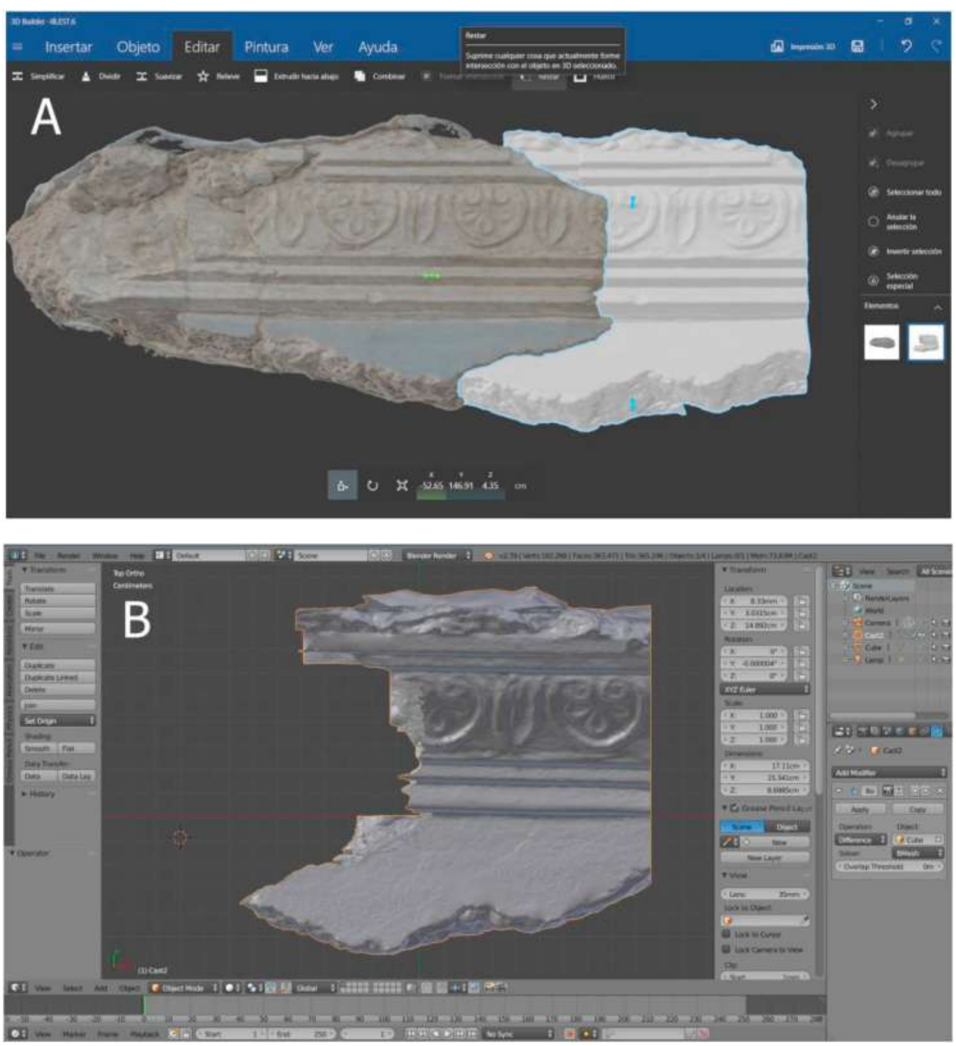

Fig. 5. A) Subtraction of part of the model using *3D Builder*; B) Final result of the reintegration.

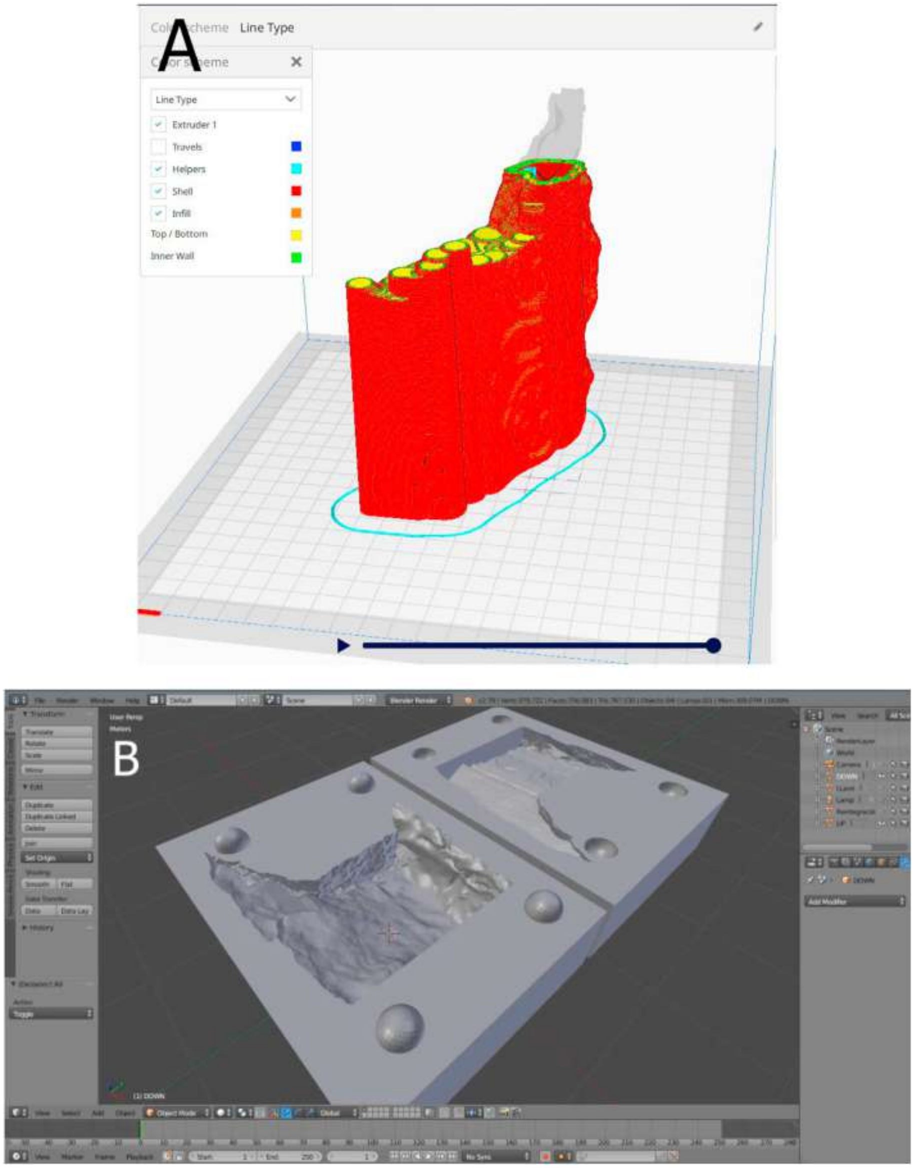

Fig. 6. A) Mold created with *Ultimaker Cura*; B) Mold created with *Blender*.

printer, Creality brand and Ender 3 Pro model, which was set for printing with *Ultimaker Cura* software (4.2.0 version). White PLA (*BQ* brand) was chosen as material for the printing, as it is an easy-to-print affordable material with good adhesion properties and minimal deformation (Fig. 8).

The printing parameters were established as follows: 0.3 mm layer height, 3-layer width for the wall, 10% fill density, 40 mm/s printing speed, 150 mm/s moving speed and plate adhesion using the raft option to guarantee that the object stuck to the plate while printing. The 3D printing of the aforementioned typological model was made with the objective of using this kind of pieces as a medium to study and promote the different decorations in Roman cornices. Besides, using the results obtained in the material analysis as a reference, we simulated the original polychrome decoration in the typological model. To do so, we used a white acrylic base and added color using natural pigments: Egyptian blue pigment (REF10060) and natural Sienna earth pigment (REFK40400) of the commercial brand KREMER PIGMENTE GMBH & CO.KG), so that the final result would be similar to the original appearance.

3. Results and discussion

In relation to the physical-chemical analyses, the samples analyzed confirm a majority presence of calcium carbonate in all diffractograms. This corresponds to the recommendations of Plinio and Vitrubio and the results obtained in other studies carried out in the Italian peninsula (Famiglietti and Scioscia-Santoro, 2001). Moreover, this analysis revealed two clearly differentiated levels of mortar, both visually and compositionally. The second mortar (the one corresponding to the attachment with the wall covering) is much more heterogeneous, has an earthy color and is composed of calcium carbonate with a considerable quantity of quartz, orthoclase and muscovite. The upper mortar is whiter, showing a majority presence of calcium carbonate with a minority presence of quartz, which does not exceed 4%.

With respect to the pictorial layer, the only pigment that could be identified is the Egyptian blue, which was fresco painted on the smooth surface of the wall. None of the studied samples of the embossed area showed the presence of pigment to add color to this decoration, thus suggesting the possibility that only lime slurry was applied to obtain a

Fig. 7. Final result of the typological model.

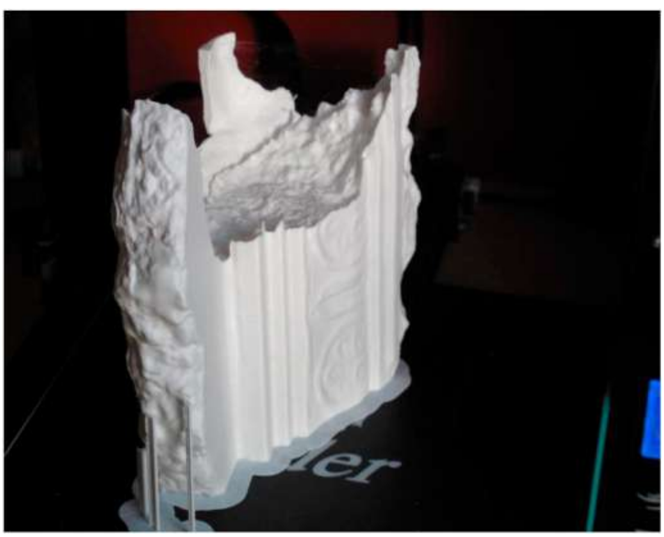

Fig. 8. 3D printing of the reintegration.

more delicate finished surface.

The use of Egyptian blue as pigment allows to conclude that the room had great richness of decorative and ornamental elements, indicative of the technical knowledge of the artists and craftsmen who created it and of the purchasing level and economic investment of those who ordered its execution (Arcos von Haartman, 2015).

Thanks to the photogrammetric model and the results obtained with the analysis techniques, it was possible to confirm that this decoration was executed with the procedures mentioned in the Materials and Methods section. The upper part would have been carried out from a wooden mold, as suggested by the repetition of the floral motifs. Some authors propose even a possible circulation of molds all around the empire to execute this type of ornaments (Cagnana and Mannoni, 2000; Guiral Pelegrín and Martín-Bueno, 1996).

The lower part would have been executed using a wooden diestock, slid over the wall after having placed the mass in the mortar. At this point, generating the model and creating its mold is of great interest, as it can be used as a teaching resource for promotion purposes, allowing the reproduction of this kind of decorations.

Regarding the photogrammetric mapping, we took a total of 137 photographs to make a complete record of the object. These images entailed a software processing time of 51 min. The model obtained had a metric accuracy of ± 0.0002 m (based on the metrics introduced between the target points), 5.3 million points and one million sides as measured by Agisoft Metashape. The digital processing of the object enabled the creation of a precise polygonal 3D model which faithfully represented the volume and the surface of the original fragment, including its texture.

The 3D model was processed with *3D Builder* and *Blender* to generate the virtual reintegration and to obtain a visual reconstruction. As a result, we modeled a piece that could be 3D printed, perfectly fitting the fragment, reproducing the decoration and providing legibility and continuity to the cornice by means of minimally invasive methodologies.

Very good results were achieved in the 3D printing of the reintegration, since it perfectly fit the limits of the lacuna (Fig. 9). Furthermore, it was a light and affordable piece, which considerably reduced the need to manipulate the original fragment. It was also a completely independent piece with no need to be attached to the original fragment, hence it perfectly respected the principle of reversibility in restoration (Fig. 9).

For its part, the typological model obtained provided a recreation of the preserved decoration in this room, which is very useful for its study and comparison with cornice fragments found in other areas of *Castulo* and in other archaeological sites in Spain or abroad.

It is important to note that the use of white PLA as printing material allowed applying a color finish afterwards, using acrylic paint and natural pigments. This possibility is quite interesting for the chromatic shade of the reintegration and the typological model, so that they can be used to resemble a reproduction of the original decorations in the rooms, and for didactical and informational purposes. Besides, it is the perfect alternative to know the real appearance of this kind of decorations in those cases where the polychrome or relief decoration is not properly preserved (Fig. 10).

Concerning the automatic generation of the mold, the main advantage is the reduction of time spent in its creation (in our case it took less than 10 min). As the mold is created automatically, we only need to enable the mold option in the programme and import the 3D model of the positive object. The final result is the negative mold sliced with the 3D

Fig. 9. 3D printed reintegration.

Fig. 10. Typological model.

printing parameters that we have already configured in the software.

However, there are also some disadvantages of the automatic creation of the mold. It is necessary to consider the orientation of the object in the build plate when creating the mold. Depending on this orientation, the result may need the use of scaffolds to support the inner part of the mold. This is a problem when the object has nooks as it will be impossible to remove the scaffolds without damaging the mold.

Nevertheless, the automatic creation of the mold is still a useful tool when combining 3D printers which can print more than one material at the same time with materials designed for scaffolding (e.g. water soluble materials) which can be easily removed afterwards.

This study demonstrates that the use of photogrammetry in combination with 3D printing helps to recognize the execution technique and the real appearance of studied fragments. The continuation of this work in other models of cornices from the archaeological site of *Castulo* or other geographical areas will be of great interest for the establishment of a classification of different decorative typologies, as well as to verify the circulation of the molds in different geographical areas. It shall also equally contribute to the promotion of and the knowledge on this kind of typologies that have so far been little studied.

4. Conclusions

The applications of digital methodologies are numerous from the point of view of conservation. The information obtained in the digital process is not only useful to know the current state of preservation of the asset but also a source of knowledge, study and promotion of this heritage. These methodologies can be followed in several areas of knowledge with no need to alter the asset, since they require minimum handle of the object.

This paper brings light to the rising importance of virtual reintegration and 3D printing techniques, as applying these methodologies for the physical reintegration of heritage would entail a reduction of material costs and less physical stress born by the piece during the intervention process. Although in this case study the photogrammetric survey has been performed using a proprietary software there are free alternatives that can be used with this purpose. This way, this research highlights that these techniques rely potentially on free and open source software for 3D modeling and digital processing, which contributes to reduce material costs and, therefore, to improve their efficiency and effectiveness, aspects of great importance for the conservation and restoration professional activity.

Lastly, there are many types of materials for 3D printing, each of them with different characteristics regarding strength, flexibility, resistance and chemical interaction, among others. These must be assessed before their use in the reintegration of heritage. Therefore, the study of the printing materials and their suitability for the physical restoration of heritage might become an innovative field of research.

Author contributions

María Higueras: Conceptualization, Software, Writing - Original Draft, Writing - Review & Editing, Visualization.

Ana Isabel Calero: Methodology, Formal analysis, Investigation, Writing - Original Draft, Writing - Review & Editing.

Francisco José Collado-Montero: Resources, Writing - Review & Editing, Supervision.

Funding

This work was supported by the Spanish Ministry of Economy and Competitiveness and the European Regional Development Fund (ERDF) [grant number HAR 2015—66139-P] and the Spanish Ministry of Science and Innovation [grant number PID 2019-105706GB-I00/AEI/10.13039/501100011033].

Declaration of competing interest

None.

Acknowledgements

We thank the Board of the archaeological site of Castulo and its director, Dr. Marcelo Castro, for allowing us to carry out this study. We are also grateful for the support of Dr. Ana García Bueno, from the Department of Painting at the University of Granada (CSIC). Likewise, we must express our gratitude to Dr. Víctor J. Medina Flórez, Chief Researcher of these projects, for his advice and management throughout the study.

References

Alderighi, T., Malomo, L., Giorgi, D., Bickel, B., Cignoni, P., Pietroni, N., 2019. Volume-aware design of composite molds. ACM Trans. Graph. 38 (4), 1–12. https://doi.org/10.1145/3306346.3322981.

Alderighi, T., Malomo, L., Giorgi, D., Pietroni, N., Bickel, B., Cignoni, P., 2018. Metamolds: computational design of silicone molds. ACM Trans. Graph. 37 (4). http://vcg.isti.cnr.it/Publications/2018/AMGPBC18/.

Almaviva, S., Lecci, S., Puiu, A., Spizzichino, V., Fantoni, R., Falconieri, M., Gagliardi, S., Chiari, M., Mazzinghi, A., Ruberto, C., Casaril, G., Bandini, G., Morretta, S., 2019. Raman/XRF/EDX microanalysis of 2nd-century stuccoes from domus valeriorum in Rome. J. Cult. Herit. 37, 225–232. https://doi.org/10.1016/j.culher.2018.11.004.

Arbace, L., Sonnino, E., Callieri, M., Dellepiane, M., Fabbri, M., Iaccarino Idelson, A., Scopigno, R., 2013. Innovative uses of 3D digital technologies to assist the restoration of a fragmented terracotta statue. J. Cult. Herit. 14 (4), 332–345. https://doi.org/10.1016/j.culher.2012.06.008.

Arcos von Haartman, E., 2015. El azul egipcio en la pintura de Cástulo (Jaén). *Anuario*. Real Academia de Bellas Artes de San Telmo 15, 91–97. https://dialnet.unirioja.es/servlet/articulo?codigo=6392697.

Balletti, C., Ballarin, M., Guerra, F., 2017. 3D printing: state of the art and future perspectives. J. Cult. Herit. 26, 172–182. https://doi.org/10.1016/j.culher.2017.02.010.

Bernardi, L., Busana, M.S., Centola, V., Marson, C., Sbrogiò, L., 2019. The Sarno baths, Pompeii: architecture development and 3D reconstruction. J. Cult. Herit. 40, 247–254. https://doi.org/10.1016/j.culher.2019.04.011.

Blitz, A., 2019. Stepping stones: virtual restoration and 3D visualisation of the tessellated 4th century Byzantine synagogue floor at Apamea on Orontes, Syria. Digital Applications in Archaeology and Cultural Heritage 15, e00108. https://doi.org/10.1016/j.daach.2019.e00108.

Brown, B., Laken, L., Dutré, P., Van Gool, L., Rusinkiewicz, S., Weyrich, T., 2012. Tools for virtual Reassembly of fresco fragments. International Journal of Heritage in the Digital Era 1 (2), 313–329. https://doi.org/10.1260/2047-4970.1.2.313.

Cagnana, A., Mannoni, T., 2000. Manuali per l'archeologia. Archeologia dei materiali da costruzione. Editrice Società Archeologica Padana s.r.l.

Davis, A., Belton, D., Helmholz, P., Bourke, P., McDonald, J., 2017. Pilbara rock art: laser scanning, photogrammetry and 3D photographic reconstruction as heritage management tools. Heritage Science 5 (1), 25. https://doi.org/10.1186/s40494-017-0140-7.

de la Torre Cantero, J., 2015. Creación de réplicas de patrimonio escultórico mediante reconstrucción 3D e impresoras 3D de bajo coste para uso en entornos educativos. Arte, Individuo Soc. 27 (3), 429–446. https://dialnet.unirioja.es/servlet/articulo?codigo=5355712.

De Reu, J., De Smedt, P., Herremans, D., Van Meirvenne, M., Laloo, P., De Clercq, W., 2014. On introducing an image-based 3D reconstruction method in archaeological excavation practice. J. Archaeol. Sci. 41, 251–262. https://doi.org/10.1016/j.jas.2013.08.020.

Delpiano, D., Peresani, M., Pastoors, A., 2017. The contribution of 3D visual technology to the study of Palaeolithic knapped stones based on refitting. Digital Applications in Archaeology and Cultural Heritage 4, 28–38. https://doi.org/10.1016/j.daach.2017.02.002.

Díaz-Marín, C., Aura-Castro, E., 2017. Making 3D implants for conservation and restoration of archaeological glass. Virtual Archaeology Review 8 (16), 103–109. https://doi.org/10.4995/var.2017.5946.

Díaz Martínez, I., Citton, P., De Valais, S., García Ortiz, E., 2018. La fotogrametría se convierte en una poderosa herramienta para la conservación y difusión del patrimonio paleontológico, vol. 20. Revista PH. https://doi.org/10.33349/2018.0.4191.

Dulieu-Barton, J.M., Dokos, L., Eastop, D., Lennard, F., Chambers, A.R., Sahin, M., 2005. Deformation and strain measurement techniques for the inspection of damage in works of art. Stud. Conserv. 50 (1), 63–73. https://doi.org/10.1179/sic.2005.50.supplement-1.63.

Echavarria, K.R., Samaroudi, M., Weyrich, T., 2020. Fracturing artefacts into 3d printable puzzles to enhance audience engagement with heritage collections. J. Comput. Cult. Herit. 13 (1), 1–22. https://doi.org/10.1145/3351343.

Erolin, C., Jarron, M., Csetenyi, L.J., 2017. Zoology 3D: creating a digital collection of specimens from the D'arcy Thompson Zoology Museum. Digital Applications in Archaeology and Cultural Heritage 7, 51–55. https://doi.org/10.1016/j.daach.2017.11.002.

Evin, A., Souter, T., Hulme-Beaman, A., Ameen, C., Allen, R., Viacava, P., Larson, G., Cucchi, T., Dobney, K., 2016. The use of close-range photogrammetry in zooarchaeology: creating accurate 3D models of wolf crania to study dog domestication. J. Archaeol. Sci.: Report 9, 87–93. https://doi.org/10.1016/j.jasrep.2016.06.028.

Famiglietti, L., Scioscia-Santoro, C., 2001. La tecnica dello stucco attraverso le fonti: tecnica d'esecuzione e caratterizzazione chimico-fisica dei materiali costitutivi. In: Conference Lo o Stucco: Cultura, Tecnologia, Conoscenza: Atti Del Convegno Di Studi Bressanone.

Fioretti, G., Acquafredda, P., Calò, S., Cinelli, M., Germanò, G., Laera, A., Moccia, A., 2020. Study and conservation of the St. Nicola's Basilica mosaics (Bari, Italy) by photogrammetric survey: mapping of polychrome Marbles, decorative patterns and Past restorations. Stud. Conserv. 65 (3), 160–171. https://doi.org/10.1080/00393630.2019.1614270.

Foramitti, H., 1980. The Use of Photogrammetry in Restoration. Conservation within Historic Buildings: Preprints of the Contributions to the Vienna Congress, pp. 57–59. https://www.iiconservation.org/node/1727.

Guiral Pelegrín, C., 2000. Aspectos técnicos pintura mural romana. La Mantería. Revista de La Escuela Taller 2, 62–70. https://es.scribd.com/document/51589228/Guiral-C-Aspectos-tecnicos-pintura-mural-romana-2000.

Guiral Pelegrín, C., Iñíguez-Berrozpe, L., Mostalac Carrillo, A., 2019. La domus de la calle Añón de Caesar Augusta (Zaragoza) y el programa decorativo del triclinium. Lucentum 38, 215–241. https://doi.org/10.14198/LVCENTVM2019.38.10.

Guiral Pelegrín, C., Iñíguez-Berrozpe, L., Sáenz-Preciado, C., Martín-Bueno, M., 2017. La decoración arquitectónico-decorativa realizada en estuco del patio porticado de la Domus 1 (Insula I) de Bilbilis (Calatayud, Zaragoza). Congress II Congreso de Arqueología y Patrimonio Aragonés (CAPA) (Colegio Oficial de Doctores y Licenciados En Filosofía y Letras y En Ciencias de Aragón).

Guiral Pelegrín, C., Martín-Bueno, M., 1996. Bilbilis: Decoración Pictórica Y Estucos Ornamentales. Institución Fernando El Católico.

Herholz, P., Matusik, W., Alexa, M., 2015. Approximating free-form geometry with height fields for manufacturing. Comput. Graph. Forum 34 (2), 239–251. https://doi.org/10.1111/cgf.12556.

Hernández-Muñoz, Ó., Sánchez-Ortiz, A., 2019. Digitalización e impresión 3D para la reconstrucción de pérdidas volumétricas en un modelo anatómico de cera del siglo XVIII. Conservar Patrimonio 30, 59–72. https://doi.org/10.14568/cp2018003.

Huang, Q.X., Flöry, S., Gelfand, N., Hofer, M., Pottmann, H., 2006. Reassembling fractured objects by geometric matching. ACM Trans. Graph. 25 (3), 569–578. https://doi.org/10.1145/1141911.1141925.

Jaklič, A., Erič, M., Mihajlović, I., Stopinšek, Ž., Solina, F., 2015. Volumetric models from 3D point clouds: the case study of sarcophagi cargo from a 2nd/3rd century AD Roman shipwreck near Sutivan on island Brač, Croatia. J. Archaeol. Sci. 62, 143–152. https://doi.org/10.1016/j.jas.2015.08.007.

Koutsoudis, A., Vidmar, B., Ioannakis, G., Arnaoutoglou, F., Pavlidis, G., Chamzas, C., 2014. Multi-image 3D reconstruction data evaluation. J. Cult. Herit. 15 (1), 73–79. https://doi.org/10.1016/j.culher.2012.12.003.

Long, B., 2019. In: Complete Digital Photography: Digital Photography Series, ninth ed. C. D. P. Press https://books.google.es/books?id=Ey4szQEACAAJ&dq=bibliogroup:%22Digital+photography+series%22&hl=es&sa=X&ved=2ahUKEwiBwIzL7PPtAhWH3oUKHd_yCP0Q6AEwCXoECAUQAg.

López-Martínez, T., 2015. Las pinturas murales del conjunto arqueológico de Castulo. Problemática de conservación y metodología de intervención. Arqueología y Territorio 12, 165–175. https://dialnet.unirioja.es/servlet/articulo?codigo=5377085.

López-Martínez, T., García-Bueno, A., Medina-Flórez, V.J., 2018. New methodology for the assessment of cleaning treatments. Applications of photogrammetry for restoration. J. Cult. Herit. 30, 117–123. https://doi.org/10.1016/j.culher.2017.09.019.

López Rodríguez, M.P., Serrano Lara, L., Expósito Mangas, D., 2017. Creación de la malla en el conjunto arqueológico de Cástulo: de la disciplina al vector. Revista Otarq: Otras Arqueologías 1 (1), 249. https://doi.org/10.23914/otarq.v0i1.97.

Malomo, L., Pietroni, N., Bickel, B., Cignoni, P., 2016. FlexMolds: automatic design of flexible shells for molding. ACM Trans. Graph. 35 (6) https://doi.org/10.1145/2980179.2982397.

Maté González, M.Á., Yravedra, J., González-Aguilera, D., Palomeque-González, J.F., Domínguez-Rodrigo, M., 2015. Micro-photogrammetric characterization of cut marks on bones. J. Archaeol. Sci. 62, 128–142. https://doi.org/10.1016/j.jas.2015.08.006.

McCarthy, J., 2014. Multi-image photogrammetry as a practical tool for cultural heritage survey and community engagement. J. Archaeol. Sci. 43 (1), 175–185. https://doi.org/10.1016/j.jas.2014.01.010.

Mostalac Carrillo, A., Guiral Pelegrín, C., 1994. Pictores et albarii en el mundo romano. Cuadernos Emeritenses 8, 137–158.

Palma, G., Pingi, P., Siotto, E., Bellucci, R., Guidi, G., Scopigno, R., 2019. Deformation analysis of Leonardo da Vinci's "Adorazione dei Magi" through temporal unrelated

3D digitization. J. Cult. Herit. 38, 174–185. https://doi.org/10.1016/j.culher.2018.11.001.

Palmas, G., Pietroni, N., Cignoni, P., Scopigno, R., 2013. Proceedings of the DigitalHeritage 2013 - Federating the 19th Int'l VSMM, 10th Eurographics GCH, and 2nd UNESCO Memory of the World Conferences, Plus Special Sessions FromCAA, Arqueologica 2.0 et Al. A Computer-Assisted Constraint-Based System for Assembling Fragmented Objects, vol. 1, pp. 529–536. https://doi.org/10.1109/DigitalHeritage.2013.6743793.

Pereira Uzal, J.M., 2013. Gestión del color en proyectos de digitalización. https://books.google.es/books/about/Gestión_del_color_en_proyectos_de_digit.html?id=XJTBngEACAAJ&redir_esc=y.

Pérez-García, J.L., Mozas-Calvache, A.T., Barba-Colmenero, V., Jiménez-Serrano, A., 2019. Photogrammetric studies of inaccessible sites in archaeology: case study of burial chambers in Qubbet el-Hawa (Aswan, Egypt). J. Archaeol. Sci. 102, 1–10. https://doi.org/10.1016/j.jas.2018.12.008.

Petrelli, D., 2019. Making virtual reconstructions part of the visit: an exploratory study. Digital Applications in Archaeology and Cultural Heritage 15, e00123. https://doi.org/10.1016/j.daach.2019.e00123.

Rahaman, H., Champion, E., Bekele, M., 2019. From photo to 3D to mixed reality: a complete workflow for cultural heritage visualisation and experience. Digital Applications in Archaeology and Cultural Heritage 13 (April), 1–12. https://doi.org/10.1016/j.daach.2019.e00102.

Resco, P.A., Carmona Barrero, J.D., Fernández Díaz, M., Serrano, P.M.M., 2014. "Fotogrametría Involuntaria": rescatando información geométrica en 3D de fotografías de archivo. Virtual Archaeology Review 5 (10), 11–20. https://dialnet.unirioja.es/servlet/articulo?codigo=5210193&info=resumen&idioma=ENG.

Rivero, O., Ruiz-López, J.F., Intxaurbe, I., Salazar, S., Garate, D., 2019. On the limits of 3D capture: a new method to approach the photogrammetric recording of palaeolithic thin incised engravings in Atxurra Cave (northern Spain). Digital Applications in Archaeology and Cultural Heritage 14, e00106. https://doi.org/10.1016/j.daach.2019.e00106.

Rodríguez Hidalgo, J.M., 2010. De la reconstrucción tradicional a la virtual. Una visión desde la Arqueología. Virtual Archaeology Review 1 (1), 163. https://doi.org/10.4995/var.2010.5140.

Salvador, I.C., Muñoz, M.A.Z., 2019. Study of wall paintings from the "mosaico de los amores" room of the ibero-roman city of Castulo. Ge-Conservacion 16, 45–61. https://doi.org/10.37558/GEC.V16I0.663.

Taglieri, G., Rigaglia, D., Arrizza, L., Daniele, V., Macera, L., Rosatelli, G., Romè, V., Musolino, G., 2019. Microanalytical investigations on a Byzantine fresco of the Dormitio virginis from Sicily. J. Cult. Herit. 40, 155–162. https://doi.org/10.1016/j.culher.2019.05.016.

Torres, J.C., Cano, P., Melero, F.J., España Acebal, M., 2010. Aplicaciones de la digitalización 3D del patrimonio. Virtual Archaeology Review 1 (1), 51–54. https://doi.org/10.4995/var.2010.4768.

Tortora, M., Sfarra, S., Chiarini, M., Daniele, V., Taglieri, G., Cerichelli, G., 2016. Non-destructive and micro-invasive testing techniques for characterizing materials, structures and restoration problems in mural paintings. Appl. Surf. Sci. 387, 971–985. https://doi.org/10.1016/j.apsusc.2016.07.023.

Vranich, A., 2018. Reconstructing ancient architecture at Tiwanaku, Bolivia: the potential and promise of 3D printing. Heritage Science 6 (1), 1–20. https://doi.org/10.1186/s40494-018-0231-0.

Waagen, J., 2019. New technology and archaeological practice. Improving the primary archaeological recording process in excavation by means of UAS photogrammetry. J. Archaeol. Sci. 101, 11–20. https://doi.org/10.1016/j.jas.2018.10.011.

Wilson, P.F., Stott, J., Warnett, J.M., Attridge, A., Smith, M.P., Williams, M.A., 2018. Museum visitor preference for the physical properties of 3D printed replicas. J. Cult. Herit. 32, 176–185. https://doi.org/10.1016/j.culher.2018.02.002.

Zangrossi, F., Delpiano, D., Cocilova, A., Ferrari, F., Balzani, M., Peresani, M., 2019. 3D visual technology applied for the reconstruction of a Paleolithic workshop. J. Archaeol. Sci.: Report 28, 102045. https://doi.org/10.1016/j.jasrep.2019.102045.