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DIGITAL AND PHYSICAL REPLICAS FOR THE STUDY AND VALORISATION OF ARCHAEOLOGICAL ARTEFACTS: THE LEAD SEAL OF POPE GREGORY IX FROM THE ARCHAEOLOGICAL EXCAVATION AT *AMITERNUM* (AQ)

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Abstract

The research presented in this paper illustrates the results of the digitisation and 3D printing process carried out on the papal seal of Pope Gregory IX, an archaeological artefact found during excavation activities at the archaeological site of *Amiternum* (AQ). The 3D model obtained from the laser scanner survey was the starting point for making some considerations on the artefact and realising its physical replica. The results achieved highlight the effectiveness of the 3D digital survey and the advantages deriving from the use of digital technologies both in the field of documentation for knowledge and analysis and in the fruition and valorisation of the archaeological heritage.

Keywords

Digital heritage, Phygital Heritage, 3D scanning, 3D printing, Knowledge and documentation, Conservation and valorisation

1. Introduction

Today, digital surveying techniques and 3D printing are valuable tools to support cultural heritage processes.

Image and range-based surveying techniques enable the acquisition of a large amount of information by returning different outputs, such as point clouds, meshes and three-dimensional models, with a high level of precision and accuracy (Picchio, Parrinello, & Barba, 2022; Sterp Moga, Hernández-Muñoz, & Sánchez-Ortiz, 2022). The digital replicas resulting from the survey process promote knowledge dissemination and information exchange since information is structured within digital content and containers that are always available and updatable (Melendreras Ruiz, Marín Torres, & Sánchez Allegue, 2021; Parrinello, Dell'Amico, & Galasso, 2022; Trizio, Demetrescu, & Ferdani, 2021). In addition, 3D models can be used to perform critical and interpretative analyses directly in the digital environment, facilitating the identification of optimal solutions to ensure the preservation of cultural heritage assets (Marra, 2023; Marraffa & Fatta, 2021).

At the same time, the development of rapid prototyping techniques has promoted the creation of physical replicas that can be used for preserving artefacts but also their valorisation and fruition (Clini et al., 2017; Fergonese et al., 2019). Physical replicas become available within museum collections to communicate the results of research through hypothetical reconstructions of archaeological artefacts, and to break down physical barriers, guaranteeing and enhancing the enjoyment of artefacts by people with physical and/or sensory disabilities (Senatore & Wielich, 2022).

The present study is part of this framework and explores the advantages of using 3D digital surveying and rapid prototyping in the field of communication and valorisation of cultural heritage, with a particular focus on archaeological ones.

The research was performed on an artefact found during excavation activities at the archaeological site of Amiternum (AQ) in the locality of Campo Santa Maria. The area, investigated since 2012 by the University of L'Aquila, which acquired the property in 2020, has returned several structures and artefacts belonging to different periods of activity (from the 1st century B.C. to the end of the 14th century) (Forgione & Savini, 2019). Two lead seals of Pope Gregory IX (Fig. 1) were found during excavation activities in 2019 and are currently stored in the Archaeology Laboratory of the University of L'Aquila - Department of Human Sciences. The two seals, 40 mm in diameter and 2.70 mm in thickness, have a different state of preservation. On both are depicted the heads of the Apostles St. Peter and St. Paul and the legend '*sPAsPE*' (*Sanctus Paulus, Sanctus Petrus*), on one face, and the name of the reigning pope, with the inscription divided into three registers in Gothic capital letters, on the second face (Redi, Forgione, & Pantaleo, 2019).

Fig. 1: Lead seal of Pope Gregory IX.

The research presented here aims to digitise the investigated archaeological artefact to facilitate its analysis and documentation in digital environment and to create a physical replica that can foster the accessibility to the cultural heritage housed in the University's Museum Complex (PoMAq) by creating new forms of enjoyment and valorisation of the assets exhibited within the Museum.

2. *State of the art*

In recent years, the processes of knowledge, valorisation, communication and fruition of cultural heritage have benefited from the advantages provided by high-performance digital technologies, such as 3D surveying tools and rapid prototyping techniques.

The application of image- and range-based surveying techniques to architectural and archaeological heritage has allowed the definition and integration of different operational procedures, which return accurate and reliable data (Melendreras Ruiz et al., 2021; Russo & Senatore, 2022). The results of 3D surveying, such as point clouds and digital models, can support the knowledge, analysis and documentation of cultural heritage and are currently extensively used in the conservation, restoration and enhancement processes of different kinds of artefacts, such as archaeological finds (Ramos Sánchez, Cruz Franco & Rueda Márquez de la Plata, 2022; Fatta & Marraffa, 2022;Marra, 2023; Brusaporci et al., 2023).

The high level of accuracy of these three-dimensional models, together with the progress achieved in the field of 3D printing, has also led to investigating the possibilities of realising physical replicas of artefacts. The different studies carried out on the topic have resulted in the definition of operational procedures aimed at the realisation of physical replicas to be exhibited in museums, for conservation and dissemination of heritage, or as support for restoration (Inzerillo & Di Paola, 2017; Gonizzi Barsanti & Rossi, 2022; Cruz Franco, Rueda Márquez de la Plata, & Pérez Sendí, 2023). At the same time, the results of these studies have also highlighted the benefits that 3D printing objects can offer in the field of restoration (Bonora et al., 2021; Parfenov et al., 2022), communication and enhancement of cultural heritage(Scianna & Di Filippo, 2019; Henriques et al., 2020).

In this context, several studies in the literature have also explored the benefits of physical prototypes for tactile exploration, aimed at promoting the accessibility of cultural heritage by persons with visual impairments and thus removing barriers to the enjoyment of cultural heritage (Sdegno & Riavis, 2020; Kantaros, Soulis, & Alysandratou, 2023).

3. *From 3D survey to physical prototype*

With the aim of encouraging documentation and fruition in a digital environment and promoting new ways of approaching cultural heritage through the creation of three-dimensional models and physical replicas, the lead seal of Pope Gregory IX was surveyed using image and range-based survey techniques.

The procedure adopted and the results obtained are described in the following sections.

3.1 Laser scanner survey

The seal of Pope Gregory IX in a better conservation state was surveyed with a range-based acquisition tool. Three different scans of the seal, with a total duration of approximately 5 minutes, were performed with the Artec Spider 3D Scanner (Tab. 1). It is a structured light scanner with blue light technology that provides, without the aid of reference markers, precise and high-resolution measurements in a short time.

The data acquired during the scan were subsequently processed within Artec Studio 17 Professional, the same application used during the scanning process, recurring to a manual procedure (Tab. 2). In particular, the three datasets were aligned by identifying three pairs of characteristic points for each scan.

Tab. 1: Overview of data acquired by the structured light laser.

Scan no.	Frame	Error	No. Polygons [M]
S01	429	0,5	1,86
S02	460	0,4	2,10
S03	491	0,4	2,73

Tab. 2: Summary of processing times.

Global registration [s]	Outlier removal [s]	Sharp fusion [s]	Texture [s]
16,6	20,6	42,1	4,63

The single scans were then transferred from a local to a global coordinate system using the global data registration, which allowed all surface to be converted in a single model. To create the 3D polygonal model of the seal, outliers, namely surface points that were too distant from the others, were removed and the sharp fusion of the different scans was performed setting a resolution value coherent with the error obtained. Finally, the texture obtained during the scanning process were created and mapped on the 3D model, obtaining a photorealistic model that provides significant information not only from a geometric point of view but also about colour information.

The processing of the scan data returned a three-dimensional model, characterised by 1.08 M of polygons, with a high level of morphological and qualitative detail (Fig. 2) that can be used in knowledge processes for the conservation and enhancement of the artefact.

Indeed, the obtained model is available in digital format and can be used as starting point for creating physical prototype by means of 3D printing.

The digital replica can be used to perform digital analyses and comparisons with similar artefacts (Fig. 3). At the same time, the sharing of the model on platforms and websites (Parrinello et al. 2022) facilitates knowledge, information exchange and the visualisation of results derived from multilevel analyses, guaranteeing an appropriate preservation of the artefact. In addition, the possibility of making available the digital replica of the artefact facilitates its use and valorisation to the public, enabling the involvement of a wider community than the current one.

3.2 Photogrammetric survey

In order to assess the effectiveness of the technique used for digitisation, it was considered appropriate to repeat the operation with the photogrammetric technique. This technique, based on SfM technology (Structure from Motion), is currently widespread because of its cost-effectiveness and adaptability to different purposes.

Various datasets of photographs were made in different ambient and light conditions. The small size of the seals, in particular the reduced thickness and the dark and shiny material, required more attempts to identify the light condition and background that would be more advantageous to ensure greater contrast and sharpness to the images. The Ag Soft Metashape software was used for model processing. The workflow involves the creation of a sparse cloud of points through the alignment of the photos, subsequent processing for the realization of the dense cloud and finally, the creation of the mesh and the texture. At the end of each step, filters were applied to increase the quality of the results.

The main difficulty encountered was to obtain unique models with both sides of the seals. Despite several attempts, this problem was found to be unsurpassed partly because of the reduced thickness of the seals and partly because the edges of the two faces of the seals show several rather marked irregularities. In addition, the edge shading condition has disadvantaged the matching of points on this portion of the object. The poor definition of clouds and meshes at the edges did not allow the matching of homologous points even proceeding manually.

Consequently, only models of the single faces of the seals could be produced.

The most satisfactory result was obtained for the face with the inscription of the best-preserved seal, of which are reported the salient data in Table 3.

Tab. 3: Photogrammetric survey: overview of data processing in Agisoft Metashape software.

	N. of points [K]	No. points(after filtering) [K]	Faces [K]	Time
Sparse Cloud	18	4	-	23''
Dense Cloud	543	460	-	12'48''
Mesh	-	-	179	19''

As for the other side of the seal, although the textured model is satisfactory, it was found that much of the information on the plastic joint is present only at the image level, resulting practically completely absent the model geometry. The results obtained for the other seal are similar to those described above but with a more evident impact of noise, probably due to the worst level of conservation.

Finally, a comparative analysis of the segmented photogrammetric model with the one obtained from the laser scanner was performed. The comparison, carried out assuming as reference the model obtained from the laser scanner and setting 0.50 mm as the maximum distance value, shows differences in the perimeter area of the seal (Fig. 4). These differences are due to the lack of information acquisition about some thicknesses during the photogrammetric process, which altered the geometry of the model in the area.

Fig. 2: Digital model obtained by structured light laser scanning (1.08 million polygons), shaded view on the left and textured view on the right.

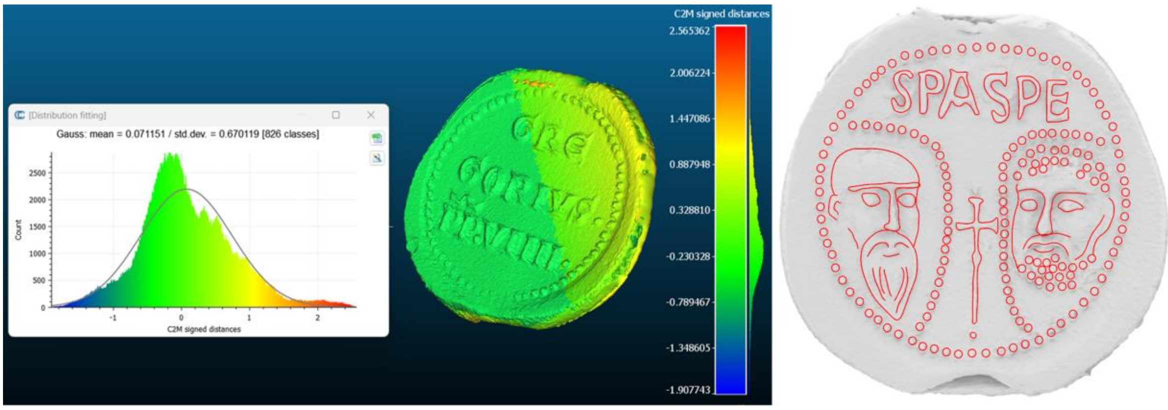

Fig. 3: Assessment of the standard deviation between the mesh models of the two lead seals, on the left; redrawing of the seal for analysis and comparison with the other sample, on the right.

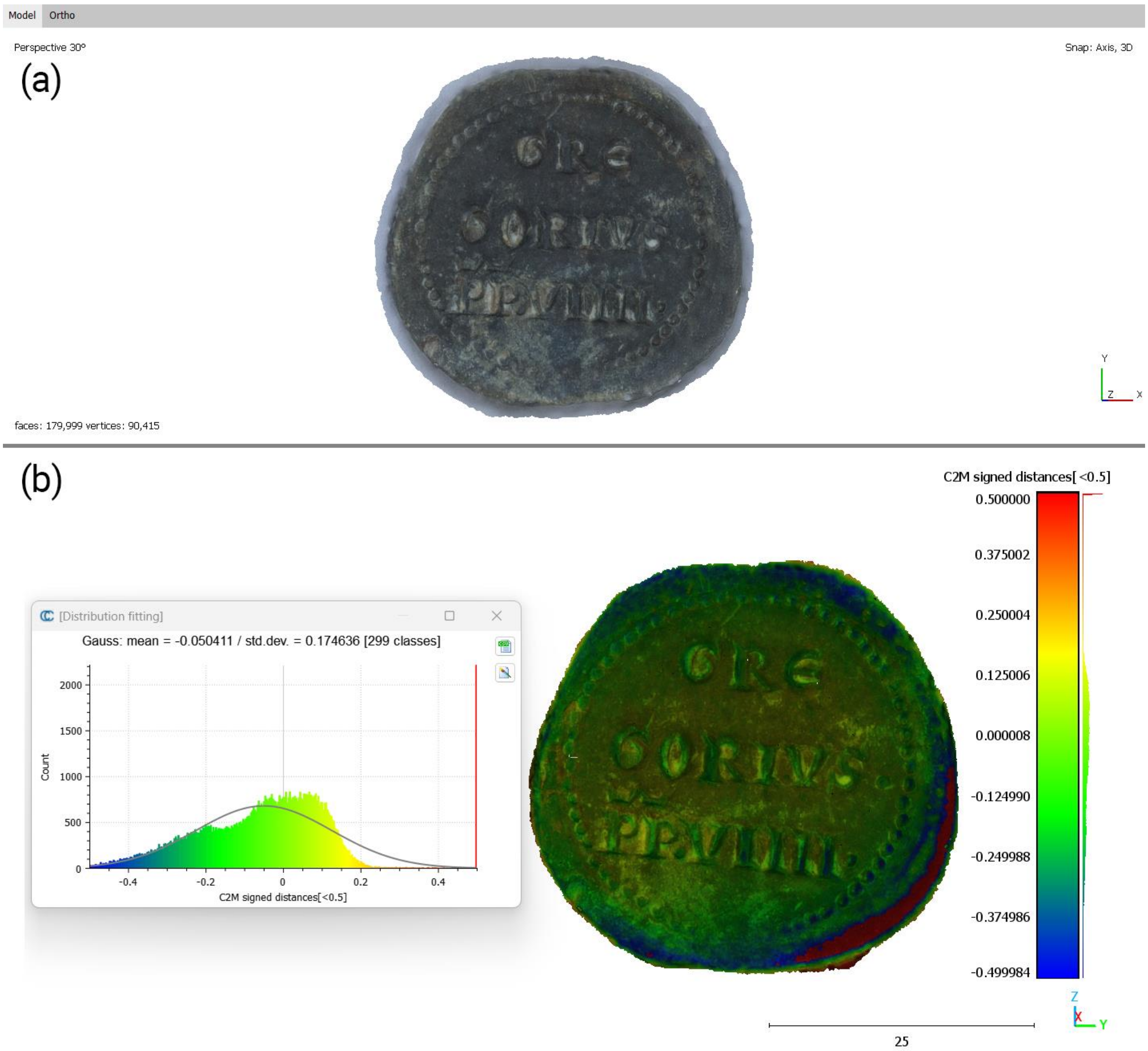

Fig. 4: (a) Textured mesh model from photogrammetric survey; (b) deviation maps obtained by comparing laser scanning model and photogrammetric one.

The issues observed with the photogrammetric survey of the analysed artefact and the results obtained from the comparison with laser scanner scanning show that, for digital documentation and 3D printing purposes, it is more suitable to use laser scanner tools for objects with small dimensions and thicknesses such as the one analysed (see section I) because these tools have a high level of accuracy and precision and return 3D models with a high level of detail in shorter times compared to those required by digital photogrammetric procedures.

3.3. The 3D-Printed Replicas

The level of detail achieved by the three-dimensional model obtained from the laser scanner survey made this the starting point for the realisation of physical replicas of the lead seal. These prototypes can encourage the fruition of the artefacts stored within the museum repositories or be used for tactile exploration by people with visual impairments [16], thus stimulating new forms of knowledge and dissemination of the PoMAq museum collection.

In this perspective, the physical replica of the seal was created starting from the 3D model converted into the Stereolithography (STL) file format.

Two different prototypes of the seal were created to assess the quality of 3D print obtained by orienting the model in two different positions (Inzerillo & Di Paola, 2017).

Therefore, the first prototype was created by importing the model obtained from the scan directly into the slicing software and positioning it vertically respect to the 3D printer's printing plate (Fig. 5a and 5c).

In the second case, the model was processed to obtain two different surfaces representative of each face of the seal.

Therefore, to create a polygonal model suitable for printing, the surfaces were further edited to remove all non-manifold edges and vertices generated by the subdivision operation and to create a closing surface. The surface processing returned two polygonal models, consisting of approximately 590K and 450K faces, which were imported into the slicing software horizontally, i.e. with the created closing surface parallel to the printing plate (Fig. 5b and 5d).

Before printing the prototypes, the final resolution of the print, defining a layer height of about 0.08 mm (high-quality print), and the filling of the shell, which is completely full due to the reduced thickness of the seals (approximately 3 mm prototype 1, and 1,5 mm prototype 2), were set. The two physical prototypes were printed with the WASP 4070 ZX printer, which uses FFF (Fused Filament Fabrication) technology, thanks to which a solid object can be created overlapping a fused filament (in this case, white ABS with a diameter of 1.75 mm) (Fig. 6a).

The estimated time for realising the first and second prototypes was about 1.5 hours, consuming 1.43 m and 1.12 m of plastic material.

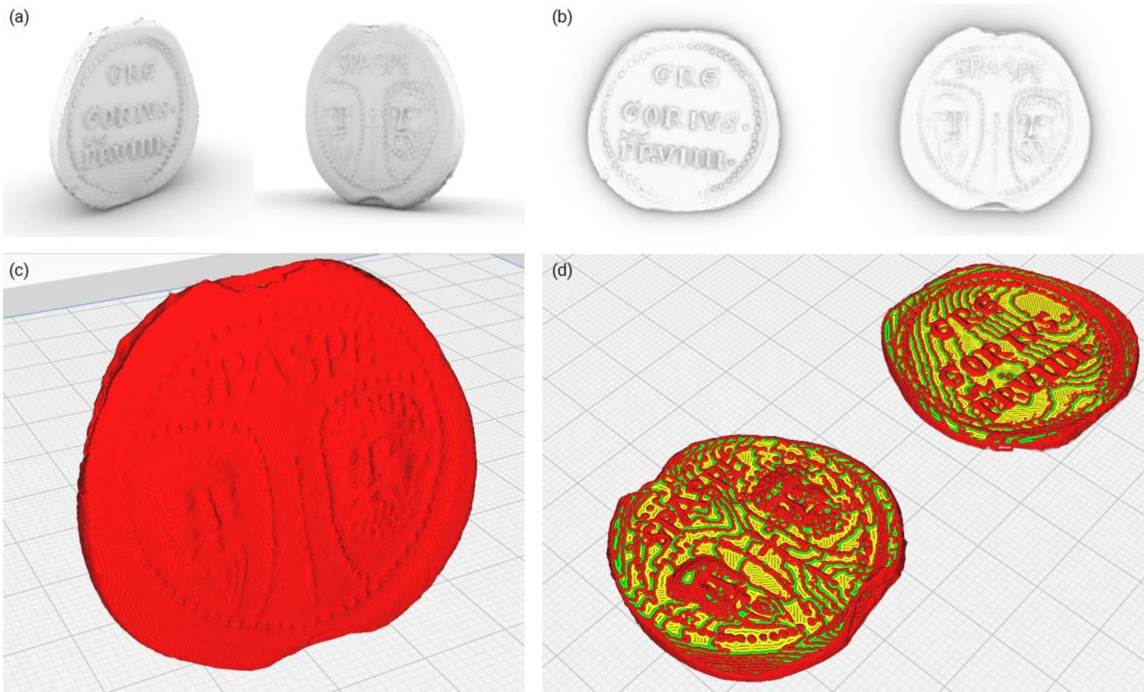

Fig 5: (a) Digital model of first prototype; (b) model decomposition into two faces; (c) first prototype imported into 3D printing slicing software; (d) second prototype imported into 3D printing slicing software.

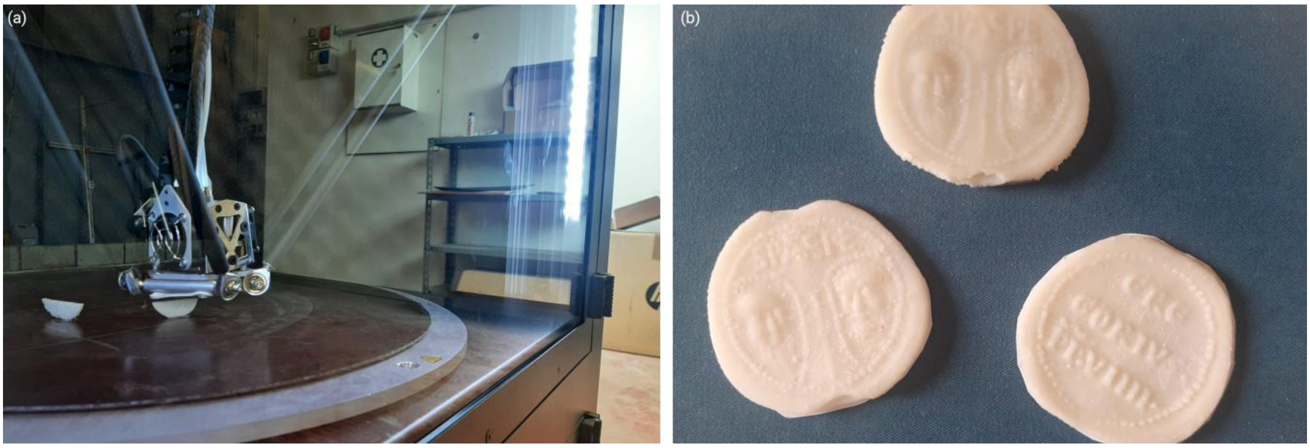

Fig. 6: (a)Printing Prototype 1 with the WASP 4070 ZX printer; (b) physical replica of the lead seal of Pope Gregory IX: above the first prototype, below the two faces of the second prototype.

The prototypes obtained show a different level of accuracy (Fig. 6b). Indeed, the extruder's displacement during the printing process creates filaments and drops of the material that make the prototype less accurate, requiring the surfaces to be finished at the end of the printing process. The physical replica obtained by positioning the model horizontally at the end of the printing has more defects and a rougher surface due to the several displacement of the extruder. The prototype obtained by positioning the model perpendicularly to the printing plate, on the other hand, presents a higher level of accuracy and allow all the details (saints' faces and inscriptions) on the two faces to be perceived, since the different layers of the plastic material are almost invisible.

4. *Final remarks*

The research illustrated, aimed at the digitisation and realisation of the physical replica of the lead seal of Pope Gregory IX found during excavation activities at the Amiternum site, made it possible to assess the effectiveness of digital survey tools, such as structured light laser scanning, and 3D printing in the field of documentation for the knowledge and fruition of the archaeological heritage.

The survey returned a digital model with a high degree of geometric correspondence to the real artefact. The level of detail achieved makes the digital replica of the seal useful for carrying out detailed analyses, such as enlargements, specific sections and comparisons with other similar artefacts, in a digital environment.

In addition, the same model was used to realise a physical replica through rapid prototyping techniques. These replicas can promote new approaches to communicating and enjoying the museum's archaeological assets, including the tactile exploration of artefacts.

Further experimentation is needed to test the communicative effectiveness of the developed prototypes by a group of visually impaired people, validating the quality of the entire process.

Although further developments are required, the achieved results confirm the potential of digital technologies in the context of knowledge and valorisation processes of cultural heritage. Indeed, while physical replicas can be used for heritage valorisation and fruition, also for tactile perceptions, digital models foster information sharing and knowledge dissemination, thanks to easily accessible and upgradable databases and platforms.

In this context, a future development of this research concerns the creation of an open science system that, through the sharing on the web of 3D models acquired through surveying, will allow the dissemination of the knowledge gathered and improve the community participation in cultural heritage processes by increasing the sense of belonging to the heritage community as foreseen by the Faro Convention (Coe, 2005).

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Credits

Although the paper was conceived as unit, Adriana Marra is the author of the sections 1, 2, 3.1 and 3.3; Luca Vespasiano is the author of the section 3.2; Stefano Brusaporci is the author of the section 4.

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