From real to real. Survey and prototyping technologies for the enhancement of cultural heritage

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Abstract

This paper examines a workflow aimed at creating tactile models that enhance the accessibility and understanding of cultural heritage for a broader audience, including individuals with visual impairments. The process involves creating replicas through subtractive prototyping, specifically milling, of a Corinthian marble capital. The replica construction starts with a detailed photogrammetric survey, which is used to guide the milling process for an accurate wooden reproduction.

The study emphasises the importance of fidelity between the replica and the original, verifying accuracy by comparing photogrammetric surveys of both. The research highlights the role of tactile models not only as tools for social inclusion but also as a means of preserving cultural heritage by replacing original artefacts exposed to deterioration risks. The methodology demonstrates that combining advanced surveying techniques with CNC prototyping can result in high-quality replicas, suitable for enhancing museum experiences and promoting inclusive cultural participation in line with the Faro Convention and Universal Design principles.

1. Intorduction

The United Nations Convention on the Rights of Persons with Disabilities, adopted on 13 December 2006, recognized the right of persons with disabilities to participate on an equal basis with others in cultural life and therefore established, among other things, that they enjoy access to cultural materials in formats accessible to them. In this context, the use of tactile models, as faithful as possible to the original morphological characteristics, is an inclusive tool that facilitates understanding and interaction with the heritage itself. Moreover, replacing the original with a copy seems to be a way to protect works often exposed to the weather and neglect, or simply to avoid deterioration due to constant interaction with the public.

The aim of this article is to verify the accuracy of a procedure for creating replicas that enhance museum artefacts and ensure inclusive use, both for the public and for people with visual impairments. The process involves the construction of the copy through subtractive prototyping (milling process) aimed at the wooden reconstruction of a marble capital, starting from the photogrammetric survey of the identified object. The photogrammetric model was used as a guide to control the machines used to produce the piece. Accuracy is verified by comparing the original and the copy photogrammetric survey, identifying a possible parameter that can demonstrate the 'degree of fidelity' of a reconstructed object.

Several studies in the literature illustrate how the use of new multisensory technologies enables the involvement of a wider audience in deeper knowledge, especially in the context of museum exhibitions; little has been written on the identification of the 'fidelity parameters' of a copy with respect to the original (Russo and Senatore, 2022). The creation of tactile models specifically for museum use is now supported by advanced three-dimensional relief and prototyping techniques that enable accurate reproductions of complex artefacts. The workflow was tested on a Corinthian marble capital, chosen for its morphological complexity, characterised by numerous undercuts and large dimensions, which presented significant challenges for the survey and prototyping.

In this context, this research explores the role of relief and prototyping technologies in the creation of tactile models, considered not only as tools for social inclusion, but also as a means to promote and enhance cultural heritage, in line with the provisions of the Faro Convention and the principles of Universal Design, which aim to define rules, methods and tools to promote inclusion and accessibility by encouraging participation in culture. The interaction between the public and the physical models becomes a way to promote critical reading of forms and improve spatial visualisation skills through tactile/visual exploration, recognising 3D constructed geometry and exploring architecture from different angles, getting closer to its forms.

The implementation of modern technologies in the field of conservation and accessibility of cultural heritage has become increasingly important, especially in museum contexts and in monumental complexes of high historical and artistic value. En fact, the digital technologies are not only tools to improve the enjoyment of cultural sites but are also necessary to promote a sustainable and interdisciplinary approach. Such approaches integrate fundamental aspects such as safety, preservation and accessibility, aiming to address a plurality of constantly evolving and increasingly heterogeneous visitor needs. Technologies such as rapid prototyping, the use of CNC milling machines and other digital fabrication techniques, combined with 3D surveying and modelling systems, make it possible to create inclusive spaces without compromising the integrity of historic buildings adapted for museum use. This cross-sectoral and technologically oriented approach not only optimises the management of cultural heritage, but also ensures a wider, interactive and respectful use of the historical characteristics of the heritage. As a result, the role of modern technologies in the cultural sector is twofold: on the one hand, they ensure the preservation and integrity of buildings and artefacts, and on the other hand, they promote accessibility by creating visitor routes and environments that adapt to contemporary needs for inclusiveness and participation, while preserving the historical and artistic value of these places.

Figure 1. The Corinthian marble capital, the subject of the applications.

1.1 Photogrammetry for cultural heritage

Photogrammetry is a particularly promising three-dimensional documentation technology for cultural heritage, and sculpture in particular, due to its ability to non-invasively capture extremely precise geometric and colour details. Recent studies show how the combined use of photogrammetry and other technologies, such as multispectral imaging and structured light scanning, enables in-depth representation of sculptural surfaces, highlighting original materials and textures in ways that exceed the capabilities of traditional techniques. Several scientific contributions have highlighted how the integration of photogrammetry with multispectral can reveal complex material properties and surface degradations, crucial information for conservators and restorers who require specific details for customised treatments (Es Sebar et al., 2023). Other research has confirmed that the combination of short-range photogrammetry and structured light scanners can offer accurate documentation of even monumental sculptures, a practice that enables the digital preservation of fine details without the risk of physical damage (Liu et al., 2012). Educational and public-use applications are further supported by photogrammetry, which allows physical objects to be recreated by 3D printing or models to be visualised in augmented reality. Today, it is possible to replicate ancient sculptures in high resolution and make them accessible for educational or exhibition purposes, facilitating the dissemination of cultural heritage even outside museums (Dovramadjiev, 2019). Some scientific work has long been aimed at addressing the optical challenges posed by reflective and complex materials such as marble and bronze, demonstrating that photogrammetry, suitably adapted, can generate 3D models that can be used by archaeologists and conservators for scientific analysis (Nicolae et al., 2014). Finally, the use of drones for photogrammetry represents a further expansion of possibilities, as it allows the acquisition of large-scale data for complex architectural sculptural elements, reducing acquisition times and ensuring accuracy at levels as low as 0.4% error (Pan et al., 2019). In summary, photogrammetry offers a wide range of opportunities for the documentation and preservation of sculptures, with employment possibilities ranging from detailed scientific documentation to the creation of physical replicas and virtual and interactive visualisation of cultural heritage.

1.2 Rapid prototyping for cultural heritage

In recent years, the use of rapid prototyping in the field of cultural heritage has seen considerable development due to the ability of these technologies to create precise replicas of fragile artefacts and historical objects, improving both preservation and accessibility. 3D printing (especially stereolithography) and CNC milling techniques have demonstrated their potential for the faithful reproduction of works of art and artefacts, allowing cultural heritage to be digitally and physically preserved and made accessible to a wider public (Senatore, 2024). Replicas are generally used in museum exhibitions to allow visitors to interact with objects that would otherwise be too fragile to be displayed. Some scholars explore the integration of tangible interaction toolkits with 3D-printed prototypes, which allow the public to touch and manipulate replicas of historical objects. This combination of rapid prototyping and interactive interfaces makes cultural heritage more accessible, especially to people with disabilities (Petrelli et al., 2023). Besides 3D printing, CNC milling is also gaining relevance in the field of heritage conservation. Although CNC milling differs from additive prototyping in its subtractive approach, it offers significant advantages for the production of replicas in harder materials or for the finishing of models produced by 3D printing (Kantaros et al., 2023); in this research, it is emphasised that CNC milling is often used to reproduce detailed surfaces and finish the edges of sculptures and objects in hard materials, such as marble or stone. This approach improves the mechanical strength of the replicas and makes it possible to get even closer to the original properties of the artefacts. The use of CNC milling is particularly relevant when working with materials that require greater precision and dimensional stability than can be achieved with 3D printing. For example, the ability of CNC to work on rigid materials such as wood or metal has been used in the reproduction of historical instruments or parts of architectural structures, where geometric precision is crucial for integration with the original (Xu et al., 2017). The combined use of rapid prototyping and CNC milling technologies is redefining the way cultural heritage is treated, preserved and made accessible. The ability of these technologies to create precise and detailed replicas that can be used for both public enjoyment and conservation purposes is opening up new opportunities in museum and cultural heritage management.

2. Methodology

The workflow devised for the creation of tactile models follows a multi-stage process, with the aim of ensuring as faithful a reproduction of the original artefact as possible using low-cost equipment.

The object identified for the application of the methodology was chosen in the context of historical buildings: it is a Roman Corinthian capital from the 2nd century B.C. (fig.1), in the possession of the Department of History, Design and Restoration of Architecture of Sapienza University of Rome; in the past it has already been used as a test for the evaluation of innovative digital survey processes (Valenti and Baglioni, 2014). The chosen subject is interesting because it consists of a formal detail whose complexity allows the process' potential to be fully tested; furthermore, the sculptural nature of the object, in any case of architectural derivation, allows the method to be extended to three-dimensional museum collections as well (Massimiliano Lo Turco et al., 2018).

The steps generally taken to make a copy are as follows:

1. Acquisition of the actual object data;
2. Processing of the data collected in step 1 to return a discrete digital model;

3. Construction of the physical copy from the digitised data;
   The steps added in this study to assess the goodness of the copy produced are as follows:
4. Acquisition of the reconstructed copy data;
5. Processing of the data collected in step 4 to return a discrete digital model;
6. Process of comparing the discrete models produced in 2 and 5.
7. In more specific terms, the procedural path we illustrate in this paper is as follows:
8. Photographic acquisition of the real object: the marble capital;
9. Restitution via Structure from Motion (SfM) process of a detailed point cloud and polyhedral model to be used for rapid prototyping;
10. Rapid prototyping by milling to obtain a 1:1 scale wooden model of a part of the object surveyed;
11. Photographic acquisition of the prototype: the wooden capital reproduced on a 1:1 scale;
12. Restitution by the SfM process of a highly detailed point cloud model of the wooden copy to be used for the final comparison;
13. Final comparison of the two point clouds and analysis of the process performed.

2.1 Surveys

One of the objectives of the research is to produce an accurate survey through low-cost processes; hence the choice of photogrammetry as a method capable of fulfilling this. In photography, the faithful representation of details is strongly linked to the control of light. Exposure is the parameter that allows for the accurate handling of light and shadows in a photographic survey. Controlling the right exposure parameters results in sharp, well-defined and detailed images: avoiding overexposure or underexposure.
The factors that enable the control of light fall into two categories:

- External factors relating to scene setup;
- Internal factors relating to the chamber parameters used.

Both types of parameters are determined during data acquisition and are variables that are highly dependent on the environment in which the surveying activity takes place.
The first category of factors aims to create uniform illumination of the object, avoiding marked shadows and reflections that could compromise the quality of the digital reconstruction of the model detected. The management of external factors is therefore aimed at eliminating variable light sources by replacing them with controllable artificial light sources, arranged in such a way as to render an object illuminated in a diffuse manner, avoiding the loss of detail.
The second category of factors brings together the variables controllable by the camera: we are talking about the optics and the so-called exposure triangle. The optics influence the shooting pattern (number of shots and distance to the object), while exposure control is still aimed at manipulating the light by operating the following parameters: camera aperture (f/stop), exposure time (shutter speed), ISO sensitivity.
The dataset obtained by operating with the right parameters does not have to be further edited when processing the data in software applying SfM. As far as specific experience is concerned, the choice of software was geared towards the pursuit of lowering process costs while still maintaining a high model accuracy (Kingsland, 2020). The outputs considered in the process are the point cloud for the final comparison and the mesh for the construction of a wooden copy using the subtractive milling process.
The surveying operation, as described in the introductory part of §2, took place twice; the first time for the actual acquisition of the form, returning a highly detailed discrete point cloud model, from which a polyhedral mesh model was derived and used as input for the milling path design software. This 1:1 scale prototype was then used as the subject for the second photogrammetric survey. In this case, the final data is the point cloud alone to be used for the model comparison process.
The two point clouds, being the result of surveying objects of similar morphology and dimensions, are deliberately devoid of the colour datum, which generally helps in the recognition of details in the model. The colour datum in this case becomes a source of confusion during the comparison phase, having on one side a marble object (the original object) on the other the wooden copy (the result of rapid prototyping) that propose different textures and colours. This is why the save and exchange files used for storing point clouds are extremely simple, having to store mainly a sequence of X, Y, Z coordinates.

2.2 Rapid prototyping

We are talking about sculptural models characterised by a formal complexity to be realised on a 1:1 scale. This condition is a constraint for the choice of prototyping method and the subsequent relief process. Scientific literature shows that additive technologies such as 3D printing offer cost and sustainability advantages over CNC milling, although the latter may excel in terms of precision and surface quality (Altadonna et al., 2023; Fico et al., 2023). In this research, the choice of a subtractive process using a CNC milling machine stemmed from the following reasons:

a) The increased diffusion of this technology at industrial and craft level;
b) The possibility of dealing with larger dimensions (in relation to the number of axes and the type of machine);
c) Precision can be achieved through the choice of the correct tools.

Furthermore, the choice of a subtractive technique is determined by the complexity of the artefact, whose shape would have been difficult to restore with additive techniques, avoiding further surface finishing processes that alter the shape and size of the object. The same milling process is potentially applicable to marble materials, enhancing the tactile experience of copying.
Regarding the choice of material, a wooden prototype was chosen in the experimental phase, having involved a company that has precision machinery for the manufacture of wooden objects for prototyping operations.
The copy was not made of the entire object, but only of a part due to problems related to the maximum dimensions achievable by the CNC milling machine of the company involved. This limit constraint is a further issue of interest, forcing the point cloud to be broken down into several parts; some of these, adjacent to each other, were selected for prototyping the object. The subsequent recomposition of the prototyped parts produces a partial copy of the object under investigation, which contains all the issues to be investigated by comparing the surveys:

- Accuracy in reproducing the details of a complex model (verifiable in one of the parts under investigation);
- Accuracy of the assembly methodology (verifiable in the juxtaposition of the manufactured parts).

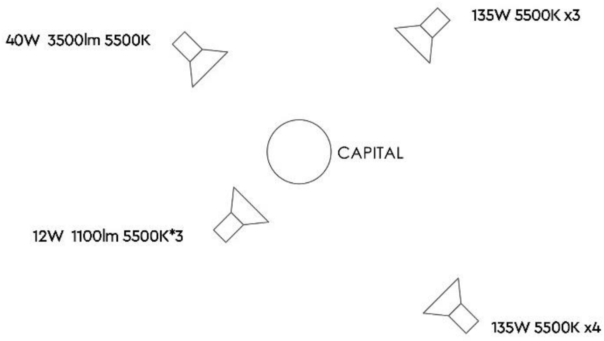

Figure 2. Capital shot set-up, model A.

2.3 The comparison of forms

The comparison phase between the point cloud derived from the relief of the original and the point cloud derived from the relief of the wooden prototype, aims to assess how faithful a copy produced through CNC milling is to the original object.
The objective is to return a tactile experience performed on the copy as close as possible to the tactile experience performed on the original object, identifying a qualified and low-cost reproduction process. Other parameters that further qualify the sensory experience performed on a copy are excluded from this morphological evaluation: we are talking about all those material characteristics that influence the temperature, weight, colour and surface texture of the reproduced object. Parameters that, in order to be compared, require other types of investigation not contemplated in this study but that stimulate further research developments.
The comparison process involves the following actions:

1. Data Preparation;
2. Alignment;
3. Analysis of differences and visualisation of results;

The point clouds of the models are imported into the software for comparison with minimal cleaning; this is due to the light control activity carried out during data acquisition.
A condition that led us, in a second automated alignment phase, to allow scaling of the point cloud of the wooden model in order to seek the best fit of the parts.
Only at this point can a comparison of the differences between the two clouds be made.
The parameter with which to construct a judgement of the quality of the copy with respect to the original object is a function of the point cloud distance of the reproduced model with respect to the reference model. The differences are visualised with colour gradients to facilitate the interpretation of the distances; another fundamental datum for understanding the goodness of the process is the error distribution.

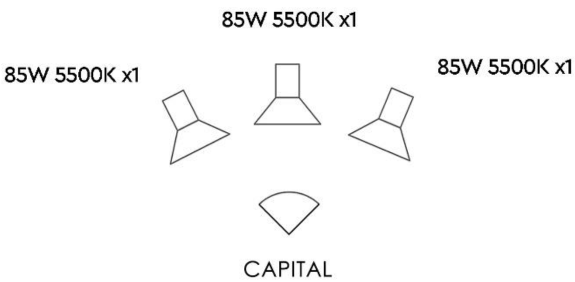

Figure 3. Set-up for the shooting of the prototype, model B.

3. Results

As anticipated in the previous paragraphs, which illustrate the reasons and methodological choices, the operational process adopted follows two main macro-phases. These are linked to the analysis of the real object, hereinafter referred to as model A, the first phase, and the prototype derived from it, hereinafter referred to as model B, the second phase. During the experimentation, certain choices were made due to technical aspects that will be illustrated below, in particular during the prototyping phase, only a portion of the capital, corresponding to one quarter, was selected and the procedure was carried out on that. Due to this selection, some of the data of the illustrated process will turn out to be of a different order of magnitude.

3.1 Data acquisition A and B

The first task was the three-dimensional measurement of the artefact, carried out by photogrammetry in a controlled environment. To ensure a high quality of the photogrammetry, a Nikon D850 camera with a resolution of 45.7 megapixels was chosen to capture the marble capital in detail. In order to maintain a uniform exposure on each shot, the camera was set in manual mode, with exposure parameters of ISO 200, and shutter speed of 1/50 s, aperture f 4.5. This last value resulted in the reduction of the depth of field. For this reason and because of the environment in which the capital is located, which has non-removable furniture, it was decided to use a lens with a variable focal length of 24-48 mm.
In order to reduce noise in the photos, a one-foot stand was used to make the shot as still as possible, but at the same time ensuring rapid movement between shooting stations.
Artificial lighting was adopted consisting of four adjustable light sources, arranged to distribute light evenly on all sides of the model (fig. 2).

A digital luxmeter was used to check the exposure values, which made it possible to adjust the distance and brightness of the lamps so as to obtain a diffuse brightness of between 510 and 560 lumens. This configuration made it possible to obtain similar exposures from different angles, reducing the need for subsequent intervention on image exposure parameters.
The shots were taken following a circular trajectory around the artefact by taking series of shots at six different heights; this allowed even the most complex parts, such as the undercuts of the capital, to be captured.
For the photogrammetry of the wooden model, the Nikon D850 was always used, ISO 200 exposure, and shutter speed of 1/40 s, f 8 aperture. This time it was possible to choose a fixed focal length because the environment in which the acquisition was carried out was uncluttered and it was therefore possible to maintain the same distance from the subject. In this case, only three light sources were set up, with adjustable intensity, because these were sufficient to ensure good illumination of the portion of model B worked on the capital forms (fig. 3). The surfaces behind, having been generated as a result of the subdivision of the model, were not considered essential for process control.

Here too, the light intensity on the surface was controlled using a digital luxmeter and an attempt was made to keep the figure in a range between 530 and 580 lumens. In this case, the brightness was increased due to the different material of the shooting subject: the use of wood, which is less light and more porous than the original marble, resulted in a different reaction to light.
During the survey campaign, 341 photographs were taken for model A and 107 for model B.

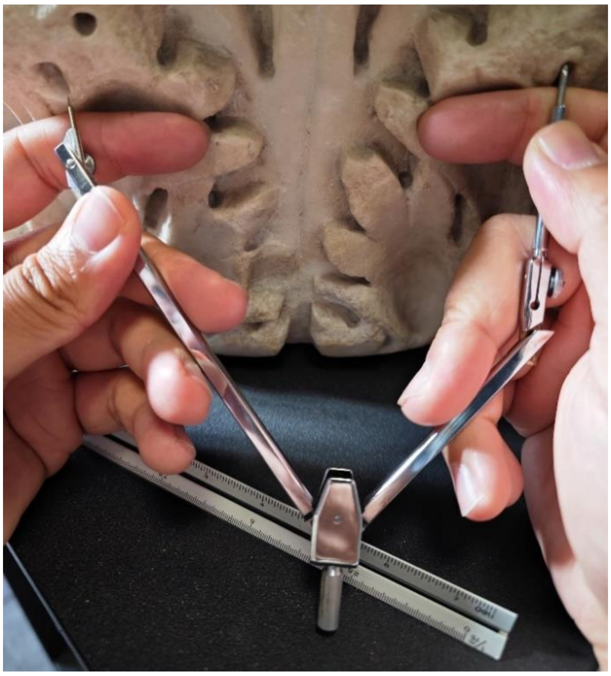

Figure 4. Taking measurements through minimum distance between two notable points.

3.2 Post-processing A and B and Rapid Prototyping

For the generation of the 3D model, Reality Capture software was used, which utilises the Structure-from-Motion (SfM) process, known for its high compatibility with images taken at variable focal lengths, thus ensuring greater accuracy in the creation of the digital model. During the phase of importing and aligning the 341 images of model A in Reality Capture, a number of parameters were set to control the results according to the computing power of the hardware instrumentation and calculation times. The software was asked for a high level of alignment and the result was the scattered cloud composed of 747,430 points that identifies an initial geometry of the object under investigation.

Once the images were aligned, a dense point cloud was generated to accurately describe the object surfaces. The dense cloud consisted of 13,879,532 points, bringing the process to the highest processing quality.

At this stage, the dense cloud model was scaled according to the actual measurements taken on the capital. For this operation, pairs of points were selected for formal characteristics, such as the edges of the acanthus leaf curls.

Measurements were taken using a compass, which allowed the distance to be measured even of points that could not be traced by a straight line (Fig. 4).

From these, the four points that could be recognised as accurately as possible were chosen, which could also be used for later comparisons and to ensure accurate scaling in the final 3D model. Then, a polygon mesh was generated from the dense point cloud, which was necessary to produce the prototype by milling.

The mesh obtained has 5,804,966 polygons (fig.5) and represents the digital model faithful to the morphological characteristics of the capital, then underwent a further process essential for CNC prototyping.

For the purposes of the experimentation and given the considerable overall dimensions of the original capital, a cube of approximately 50 x 50 x 50 cm, it was decided in the first instance to carry out the process on only a portion of the capital. The criteria that guided the selection of the portion of the capital aimed to select the most complex portion of the artefact, in which undercuts, perforated and cantilevered elements were present. The mesh model was divided through two mutually perpendicular planes passing through the centre; the mesh of a quarter capital was thus obtained and used for the prototyping of

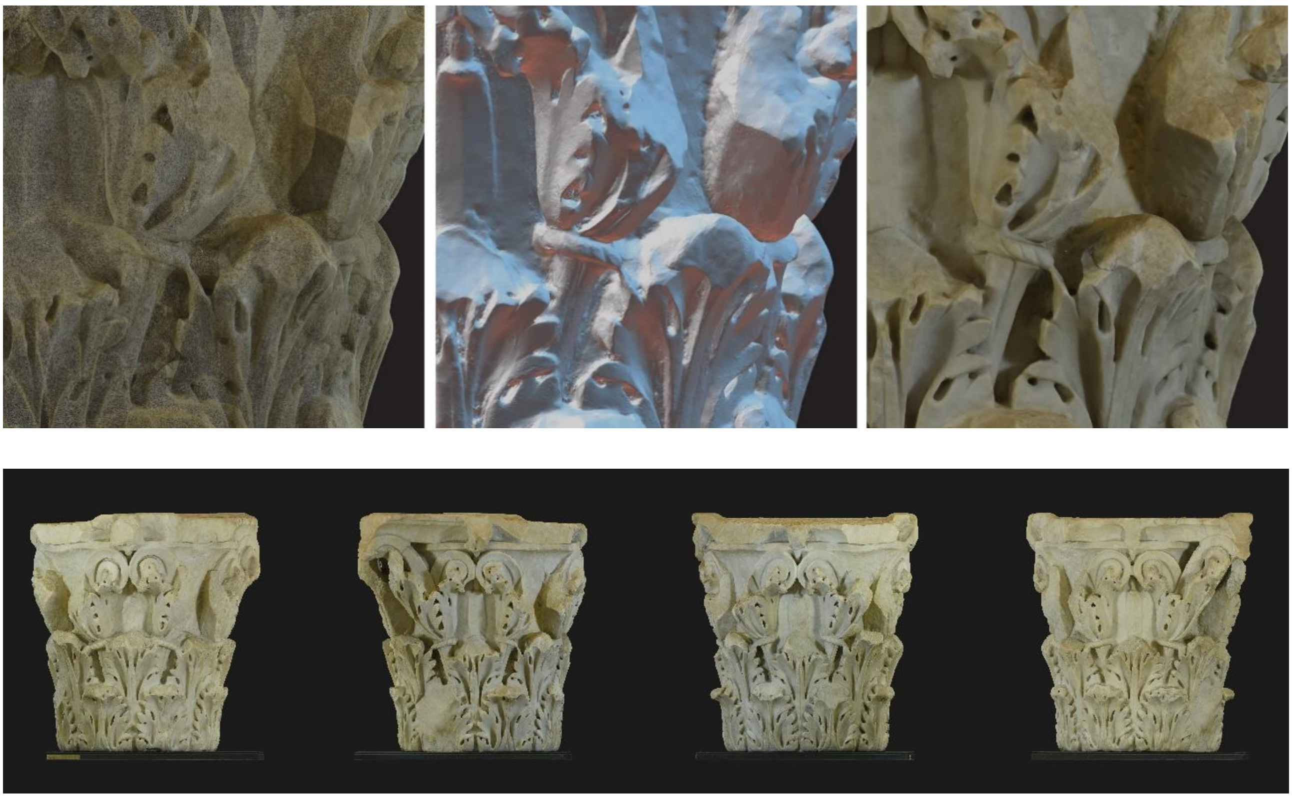

Figure 5. Model A: dense cloud (right), mesh (middle), textured mesh (left) and 4 views from the photogrammetric model.

Figure 6. Phase two of prototyping, semi-finishing step.

Figure 7. Model B assembled.

model B. Due to the technical limitations of the CNC milling machine, which allows machining of a maximum of 30 cm per side, it was decided to further subdivide the model into four more parts to facilitate the machining process.

The tool used for prototyping was a 5-axis CNC milling machine, which was useful in the machining process for the creation of complex, precision three-dimensional models. This made it possible to machine angled and concave surfaces, such as undercuts, without the need for manual repositioning of the material. The milling steps were as follows:

- first pass (roughing), a 10 mm diameter cylindrical cutter was used, an oversize of 2 mm was maintained; machining time was 2.5 hours.
- second pass (semi-finishing), a 6 mm cylindrical cutter was used, the oversize was reduced to 1 mm; machining time was 1.5 hours (fig. 6).
- third pass (finishing), a conical ball-head cutter with a 30 degree angle and 0.25 mm radius was used for finishing details; machining time was 8 hours.

During the finishing phase, efforts were made to avoid manual intervention on the model, limited to the removal of residual burrs from machining, which could have an impact on the overall accuracy.

When assembling the four machined sections, a misalignment emerged in the two upper parts, caused by a mismatch in the machining of the joint edges. This resulted in a visible error in the final model, which is the main point of divergence in the overall accuracy (Fig. 7).

Following prototyping by milling and subsequent gluing, the B-model underwent a new photographic acquisition phase, described above. Subsequently, the 107 photos were processed in the photogrammetric process.

Again, the generation of the model using SfM was carried out with Reality Capture, using the same parameters applied to the marble model to ensure uniformity in the results. During this process, the measurement and scaling steps of model B were repeated; the same 4 points selected in model A were identified for this activity. The dense point cloud obtained by this process consists of 6,559,595 points (Fig. 8).

Figure 8. Model B point cloud.

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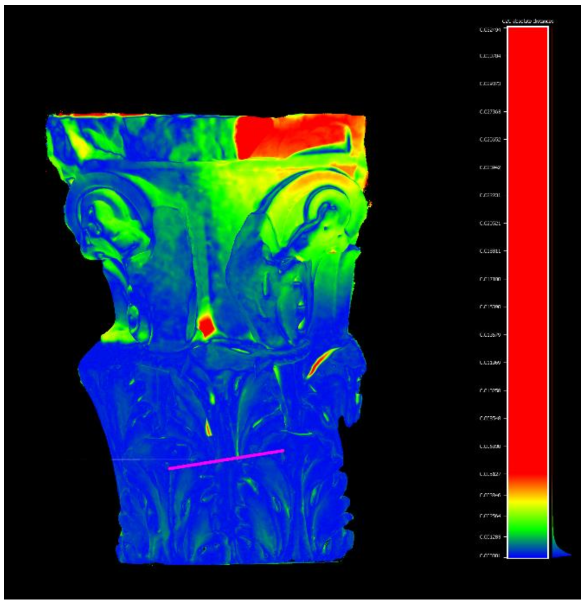
Figure 9. Overlay of the two models.

3.3 Comparison

Finally, to verify the entire process, the digital models derived from the two reliefs were then compared to verify the accuracy of the wooden copy and confirm the quality of the workflow, ensuring that the replica is indeed faithful to the original and suitable for tactile use.
To do this, two point clouds obtained from the photogrammetric process within the Cloude Compare software were compared.
The first step within the digital environment was the alignment of the two models, keeping model A as the reference (fig. 9). This step already returned an important datum in that for a perfect alignment, model B was scaled in relation to the reference model by a factor of 0.997217. The dimensional variation is due to exceptions adopted during the process; we know that the SfM operation requires the knowledge of certain measurements or the topographical beating of certain points to be identified on the original and the copy. It was not possible to identify pairs of homologous points on similar models due to the small variations in shape and the absence of texture, which normally facilitates the recognition of real parts on the cloud.
The portion of the prototyped wooden model is composed of four parts, a condition that influenced the relationship between copy and real: the gluing between the parts presupposed the addition of material, leading to possible slippage between the elements; the survey of the wooden model photographed this condition three-dimensionally. For this reason, an initial alignment related a selected constellation of points in one of the prototype parts to points in homologous areas on the cloud of the real model. A main part was then identified on the point cloud of the wooden model in such a way that, assuming a perfect reproduction of the individual wooden parts, any deviations between the two data could be attributable to the accuracy used during the gluing of the wooden portions.
The software was then asked to evaluate the distance between points, returning a very good fit between the two point clouds where the maximum distance is 0.0348 m, and the average distance is 0.0003 (fig. 10).
The comparison provides useful information and it can be seen that the greatest distance is all distributed in the upper part of the model. This could be due to two factors: the first to the distribution of the reference measurements, positioned in the lower part, and the second to the assembly phase of the four pieces that make up model B in which there were practical difficulties in gluing
.

4. Conclusions

This study demonstrated how the combination of photogrammetric surveying and subtractive prototyping through CNC milling can produce extremely faithful replicas of complex artefacts, ensuring both the preservation of cultural heritage and an accessible and inclusive experience. The described workflow proved effective in reproducing complex morphological details of a Corinthian capital, offering a viable and low-cost solution for the creation of tactile models.
The results confirm that such replicas can be used to enhance the museum experience, allowing a wider public, including individuals with visual impairments, to interact with cultural heritage. Furthermore, replacing originals with tactile replicas helps to preserve historical artefacts from wear and tear and physical damage, promoting a sustainable approach to heritage management.
However, the study revealed certain limitations in the assembly phase of the prototyped sections, which introduced discrepancies in the overall fidelity of the model. To address this problem, future developments could focus on the use of multi-axis CNC



1	Min dist.	0
2	Max dist.	0.0300191
3	Avg dist.	0.000348592
4	Sigma	0.00152811
5	Max error	0.00250159

Figure 10. Comparison of the two poin clouds.

machines, such as 7- or 9-axis machines, which would allow the milling of unique parts even for complex objects, reducing the need for joints.

In parallel, the adoption of advanced joining techniques and pre-assembly digital simulations could further improve the accuracy of replicas. Another promising area of research concerns the integration of additive technologies, such as 3D printing, with subtractive techniques to improve reproduction efficiency and fidelity. These synergetic approaches could optimise the process, enabling the creation of more accurate and sustainable tactile models. Other research developments could include the use of innovative and sustainable materials capable of replicating not only shape but also texture and perceived temperature, making the tactile experience even more immersive and faithful to the original. Furthermore, advanced techniques for analysing the differences between original models and replicas could help create new standards of fidelity for replicas.

Finally, protocols could be developed to test the effectiveness of these replicas in museum settings, analysing their impact on the visitor experience and testing how different audience groups interact with the haptic models. These studies could provide valuable data to further adapt and optimise the workflow, facilitating a large-scale adoption of these technologies for accessibility and heritage enhancement.

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