Unwrapping a Baroque Masterpiece: A Planar Representation for the Apse of Santa María del Temple in Valencia

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Abstract

This study presents a workflow for the documentation and morphological analysis of curved frescoed surfaces, combining terrestrial laser scanning (TLS) with computational imaging techniques. The case study focuses on the apse of the Church of Santa María del Temple in Valencia (Spain), decorated in 1770 with Palladian motifs. The objective is to produce a planar and interactive representation of the surface, overcoming the operational limitations of traditional Reflectance Transformation Imaging (RTI). The methodology employs a Trimble TX6 TLS to rapidly record a high-density point cloud within minutes. The dataset is then processed using open-source software tools (CloudCompare, MeshLab, Blender, Relight) to reconstruct a detailed mesh and generate a high-resolution normal map (NM), which is transferred onto a low-poly model. A digital RTI dome consisting of 49 spotlights is built in Blender, producing a sequence of rendered images that are subsequently processed to create an easy-to-use Virtual RTI (V-RTI). This approach enables the clear identification of degradation features and subtle morphological irregularities that are not easily detectable through conventional methods. The proposed workflow proves to be effective for qualitative analyses, simplifying targeted conservation interventions, especially in architecturally complex contexts where traditional techniques are unfeasible or hardly applicable. V-RTI thus represents a valuable complementary strategy for non-invasive cultural heritage (CH) diagnostics.

1. Introduction

The preservation of cultural heritage (CH) requires the simultaneous involvement of professionals from a variety of disciplinary fields. The scientific community engaged in CH documentation is currently working to redefine these interdisciplinary approaches, addressing the complex challenges of data interoperability. This involves not only generating informative content but also developing a shared technical language capable of connecting research sectors that may appear distant, yet are in fact closely linked. At the same time, the documentation process increasingly relies on scientific techniques—belonging to archaeometry—which are often complementary and benefit from recent technological advances in both hardware and software.

1.1 Archaeometry as a tool for the conservation of CH

Archaeometry is an interdisciplinary research field that integrates methodologies from the physical, chemical, and engineering sciences in the analysis of CH, with the aim of supporting the understanding, conservation, and enhancement of historical and artistic objects. In this context, 2D and 3D survey technologies have become essential tools for the non-invasive and high-precision acquisition of the geometry and conservation state of historical buildings, artworks, and archaeological artefacts.

In the specific context of studies on frescoes and wall paintings, such techniques are commonly employed in the initial diagnostic and analytical phases and are later used to support the planning of conservation and restoration interventions.

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Although a wide range of 2D and 3D acquisition methods—such as multiband photogrammetry (Di Iorio et al., 2025, Es Sebar et al., 2023), multispectral imaging (Laureti et al., 2019), thermography (Patrucco et al., 2022), structured-light scanning (Croci et al., 2024), spectroscopic analysis (Ricci et al., 2023), and tomography (Zhan et al., 2021)—are now widely used as tools for both metrological and archaeometric assessment (Sebar et al., 2020, Fiocco et al., 2021), this paper focuses on two techniques based on distinct yet complementary technologies: terrestrial laser scanning (TLS) and Reflectance Transformation Imaging (RTI) for the study of surface features.

1.2 TLS and RTI applications in CH

Among the main applications of TLS in the field of CH, several key areas of intervention can be identified, each contributing significantly to documentation, analysis, and conservation practices. One of the most widespread applications is the metric documentation of painted surfaces, where high-resolution 3D models—generated through TLS or photogrammetry—allow for the precise recording of surface irregularities, such as deformations, pigment detachments, and structural issues. These digital models serve as essential tools for monitoring the progression of deterioration over time and for planning targeted conservation efforts (Priego et al., 2024, Remondino et al., 2011, Truong-Hong et al., 2022).

Equally important is the architectural survey of monumental complexes and archaeological sites. Through TLS and drone-based photogrammetry, it is possible to produce accurate 3D models of historic buildings and archaeological remains. These models enable detailed morphological and structural analyses, facilitate stratigraphic studies, and support the creation of digital reconstructions that are useful both for research and dissemination purposes (Armesto-González et al., 2010, Diara and Roggero, 2023, Lerma et al., 2010).

In the realm of archaeological research, 3D data also play a central role in the digital reconstruction of ancient contexts. When integrated into GIS systems or virtual environments, these data allow for a spatial understanding of ancient settlements and offer the possibility to virtually recreate lost or partially preserved environments in immersive formats, thereby enriching both academic research and public engagement (Cipriani and Fantini, 2017, Campanaro et al., 2016).

Concurrently, RTI—situated between the 2D and the 3D domains—is also employed across multiple contexts, providing valuable surface information for a wide variety of objects and materials. Commonly, it is used for the documentation and analysis of epigraphic and inscribed surfaces, such as ancient tablets, stone inscriptions, and coins, where it enhances the legibility of worn or eroded markings (Min et al., 2021, Earl et al., 2011). This technique is also frequently applied in the study of artworks and painted surfaces, particularly for the investigation of fine surface textures, tool marks, and subtle features that are not easily visible under standard lighting conditions (Min et al., 2020, Manfredi et al., 2014).

Although these techniques are widely used for various purposes, they are often applied separately. For this reason, the present study seeks to combine both approaches in order to merge the strengths of each methodology, thereby extending their application to a broader range of specific and complex scenarios. Recent studies have explored this direction by combining the two approaches to enhance the potential of different technologies. (Laurent et al., 2025) quantitatively compares 3D models generated using various techniques—TLS, photogrammetry, and photometric methods—and subsequently proposes a new hybrid workflow for surface analysis. Similarly, (Morita et al., 2024) investigate the possibility of improving micro-detail in 3D models by enhancing surface texture through the application of normal map (NM) derived from RTI data. The hybridization of these techniques thus appears to open new avenues for in-depth analysis across various cultural heritage applications.

1.3 Research aims

However, one of the main limitations in the use of RTI is the need for sufficient space around the subject to properly position the light sources. Additionally, it is difficult to apply this technique effectively to non-planar surfaces, which restricts its use to areas of small to medium size. Moreover, one of the most significant constraints of this method is that it can only be implemented in easily accessible locations, where transporting and setting up the required equipment is feasible. To overcome these challenges, (Krátký et al., 2020) proposes an approach that involves the use of drones for aerial imaging to produce RTI for elevated subjects.

Nevertheless, this raises several important questions: how can RTI be effectively applied to a curved surface? How can the technique be adapted to large-scale subjects—especially when working within spatial constraints—to extract qualitative and quantitative data on the surface morphology? Is it possible to develop a workflow that addresses these challenges while relying on rapidly acquired data? Therefore, the approach presented in this study proposes the combined use of TLS and RTI to produce a Virtual RTI (V-RTI), by exploiting surface unrolling [Figure 1].

Recent studies have explored this field by experimenting the combination of photogrammetry and RTI in various contexts for the analysis of stone surfaces, yielding promising results that suggest the potential for extending this methodology to more challenging applications, tools, and environments (Greaves et al., 2020, Di Iorio et al., 2024).

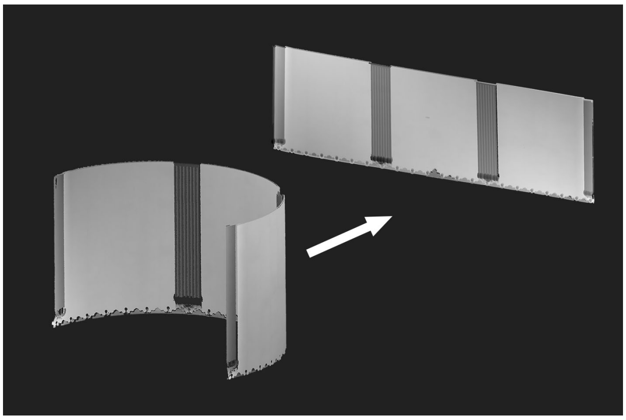

Figure 1. Conceptual synthesis of the unrolling procedure.

2. Methodology

2.1 The context

This study presents the preliminary results of a 3D survey carried out in the Church of Santa María del Temple (Valencia, Spain). The Church, part of an architectural complex built between 1761 and 1770, was designed in the Neoclassical style by Miguel Fernandez, a pupil of Francesco Sabatini. The structure reflects strong Italian Neoclassical influences and is of particular historical importance for Valencia, because the Church houses significant artworks, including an apse fresco painted in 1770 with Palladian motifs by Italian architect Filippo Fontana. The artwork, previously documented through a high-resolution 2D campaign published in 2018 (Cabezos-Bernal et al., 2018), underwent a 3D survey using TLS to collect morphological data, reconstruct its history, and develop conservation strategies.

The fresco, positioned at a considerable height, is challenging to observe directly [Figure 2]. Its large size, combined with limited space and the inability to use scaffolding, poses difficulties in gathering detailed information. In addition, the semicircular shape of the apse prevents a simultaneous overall view and complicates the acquisition of raking-light images, which are useful for surface analysis.

2.2 Data acquisition

The Church of Santa María del Temple is a significant and frequently visited place of worship for the citizens of Valencia. Due to its cultural importance and the impossibility of conducting operations during closing hours, the data acquisition had to be carried out with minimal disruption to the sacred functions of the site. These constraints informed the selection of the most suitable instrumentation, aiming to maximize the amount of data collected without compromising either quality or the potential for information extraction during post-processing. As

Figure 2. The Church of Santa María del Temple (A) and the Apse behind the main altar (B).

a result, the chosen acquisition system was a phase-shift laser scanner (Trimble TX6, Trimble Inc., Westminster, CO, USA), capable of rapidly capturing detailed scans over large areas with a relatively low level of noise (Table 1).

Distance measurements	Phase shift
Extended range	120 m
Horizontal and vertical range	360°/317°
Point spacing	11.3 mm at 30 m
Acquisition speed	500,000 pts/s

Table 1. Trimble TX6 technical specifications

By setting the scanner to Level 2 (point spacing of 11.3 mm at a distance of 30 meters), a total point cloud of approximately 138 million points was acquired, of which 19.8 million specifically pertain to the apse. The survey was conducted from a single scanning position, strategically located at the center of the ideal circumference defined by the curvature of the wall. This setup was chosen to ensure the most uniform resolution possible across the entire scan. As only one scan was recorded, no registration targets were placed in the scene, since there was no need to align multiple datasets. The scanning process itself took about 5 minutes, while the complete session—including setup and dismantling of the laser equipment—required approximately 40 minutes. The collected data were subsequently processed following the procedures described in the next sections.

2.3 Data processing

The methodology relied exclusively on open-source software—except for the Trimble software used in the first stage to convert the laser point cloud—in order to ensure broad accessibility and reproducibility. Specifically, CloudCompare (v2.13.1) was used to identify the most suitable geometric primitive for planar development and to calculate standard deviation values; MeshLab (v2023.12) was employed for mesh generation and optimization; Blender (v3.5) was used for UV mapping and for rendering the model; and Relight (v1.3.0) was employed for processing the V-RTI. The following sections describe the procedures to produce each output within the workflow, using a high-end workstation (Windows 10 Pro, Intel Xeon Gold 6128 3.40GHz, RAM 192GB, NVIDIA Quadro P4000).

2.3.1 Primitives and unrolling The raw data acquired through TLS were exported in .e57 format using Trimble RealWorks (version 11.0). Since the point cloud exhibited a very low level of noise, no filtering for noise reduction was applied. This choice was deliberate, aiming to evaluate the reliability of the proposed method regardless of the initial data quality.

The next step involved the identification of the geometric shape (primitive) that best approximates the actual surface of the object, to be used as a reference for the planar representation. However, performing this operation on the full-resolution point cloud would be highly demanding in terms of both processing time and hardware resources. For this reason, it was necessary to downsample the dataset, reducing point density to obtain a lighter and more manageable version, while still maintaining sufficient accuracy to represent the morphology of the element.

After importing the high-resolution scan into CloudCompare (v.2.13.1) [Figure 3(a)], a subsampling operation was performed using the Subsample tool [Figure 3(b)]. At this stage, it is crucial to determine an optimal point spacing value, striking a balance between data manageability and geometric accuracy. The goal is to reduce the size of the point cloud to make it more efficient to process, while still maintaining sufficient density to reliably approximate the original shape and avoid the loss of meaningful information.

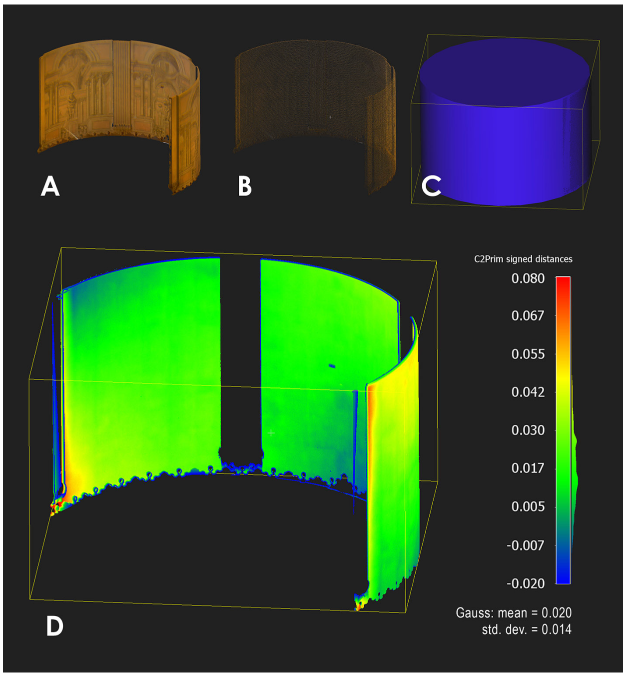

Figure 3. Steps to calculate the RMSE on the cylindrical primitive used to unroll the Apse. (A) original point cloud; (B) subsampled point cloud; (C) fitted least-squares cylinder; (D) Standard Deviation.

In this specific case, a point spacing of 0.01 m—meaning an average distance of 1 cm between selected points—was adopted. This yielded a new point cloud of approximately 800,000 points, offering a practical compromise between detail richness and computational efficiency compared to the original dataset.

The geometric primitive was then computed using a subset of 200,000 points, to which the RANSAC algorithm was applied. The result was the identification of the cylindrical shape that best fits the geometry of the apse. The associated parameters—radius, height, and axis angle—were automatically calculated and stored as a new item in the elements tree [Figure 3(c)].

To assess the quality of the identified geometric primitive, the distance between the original point cloud and the primitive was calculated. This comparison yielded the Root Mean Square Error (RMSE), using the Compute cloud/Primitive distance function in CloudCompare. The RMSE value provides a quantitative indicator of how accurately the primitive fits the actual geometry of the surface [Figure 3(d)]. Once validated, the primitive is used for the planar development of the point cloud, applying the Unroll command.

2.3.2 Meshing Following the unrolling, the high-density point cloud [Figure 4(a)] is imported into MeshLab (v2023.12) for the generation of a triangular mesh. Once the normals of each vertex are computed—using Compute normals for point set—the meshing is carried out using the Screened Poisson algorithm, with a Reconstruction depth value set to 13, resulting in a high-resolution mesh model [Figure 4(b)].

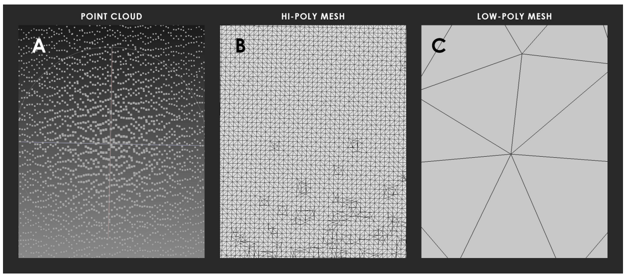

Figure 4. Different views of the same area of the digital replica: (A) point cloud; (B) high-resolution mesh (50 millions polygons); (C) mesh after the decimation (140,000 polygons).

The resulting model is composed of approximately 50 million polygons, ensuring a high level of detail. Although other algorithms such as Ball Pivoting are available for mesh reconstruction, the latter proved to be significantly more time-consuming compared to Screened Poisson. For this reason, it wasn't adopted in the present study.

Once the mesh has been generated, it is advisable to proceed with an optimization phase to improve its quality and usability in the subsequent processing stages. Among the most common operations is the removal of polygons not belonging to the main geometry, as these may cause visual artifacts during rendering. It is also important to identify and eliminate polygons that do not correspond to the actual surface or that exhibit topological errors, using the Repair Non Manifold Edges function.

The workflow in MeshLab ends with the reduction of the total number of polygons using Quadric Edge Collapse Decimation—applying a ratio of 1:350—followed by the export of the model in .obj format. This results in a lighter and more manageable mesh, consisting of approximately 140,000 polygons [Figure 4(c)].

2.3.3 Normal Map and image rendering The production of an RTI involves calculating a NM based on the analysis of each point's shadow generated by a light source moved to different positions from one image to another. In this workflow, instead of using real photographs, renders of the 3D model—generated in a virtual environment that faithfully simulates the light movements of a traditional RTI—are employed. Before starting the rendering process, it is necessary to transfer the high-resolution details onto the decimated model. Decimation inherently causes a significant loss of fine detail, which can introduce visual artifacts and compromise the method's effectiveness. To mitigate this issue, a high-definition NM should be generated from the original model and then applied to the simplified one. This procedure was performed in Blender (v3.5). Before any operation, it is essential to ensure that the two models—high-resolution and low-resolution—are perfectly superimposed in the 3D space of Blender. The low-resolution model must first be prepared to receive the NM generated from the high-resolution one. To do so, the polygonal structure of the low-poly model needs to be reorganized. This preparation involves creating a new UV map, which is defined by the placement of seams: the latter are guide lines that enable the surface of the 3D model to be unfolded onto a 2D plane, as if unrolling the object's "skin" for a flat representation. Seams are manually drawn lines on the mesh indicating where to cut it before unfolding onto a plane. This is a crucial step in 3D modeling that helps produce a well-organized texture—and NM as well—especially when the model is built from real-world data—as in photogrammetry or laser scanning. The NM can then be generated (Bake Normal Map) using Cycles rendering engine (image resolution 8192×8192 px), and applied to the model via the nodes control panel, thus transferring the high-resolution detail onto the low-poly model.

At this stage, the model is ready to be rendered for the V-RTI. The virtual lighting setup consists of 49 light sources, which are arranged in a dome configuration. Each light source is directed towards the center of the model. [Figure 5].

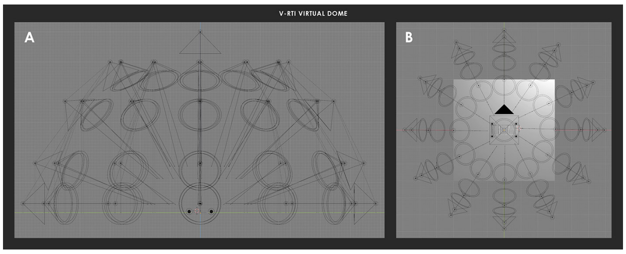

Figure 5. The virtual lighting dome built on Blender for the creation of the Virtual RTI renders (A); the dome seen from a nadiral point of view (B).

The model is placed centrally at the base of the dome, together with four black reflective spheres placed close to its borders. The spheres must have a resolution of at least 250 px in the final render and defined by a shiny material (Roughness 0.1, Metallic 0.8).

The setup also includes an animation that synchronizes the rendering of images with the switching on and off of the spotlights. The model is rendered from a nadiral camera set in orthographic view, and by using the EEVEE engine (sampling value 1, image resolution 12288×12288 px), producing an sRGB .jpg file every 7 seconds for each light position.

2.3.4 Virtual RTI Subsequently, renders are imported into Relight (v1.3.0), a software that employs multiple algorithms to compute the reflectance of each pixel, relying on the incidence of light. Relight enables the virtual manipulation of light direction of an object captured by a fixed camera, thereby enhancing surface details that would be difficult to discern in a static photograph. Each frame is then imported into the software, where the four reflective spheres must be identified to enable the determination of the spatial positions of the spotlights, thus computing the V-RTI [Figure 6]. The resulting output can be seen using RTIViewer.

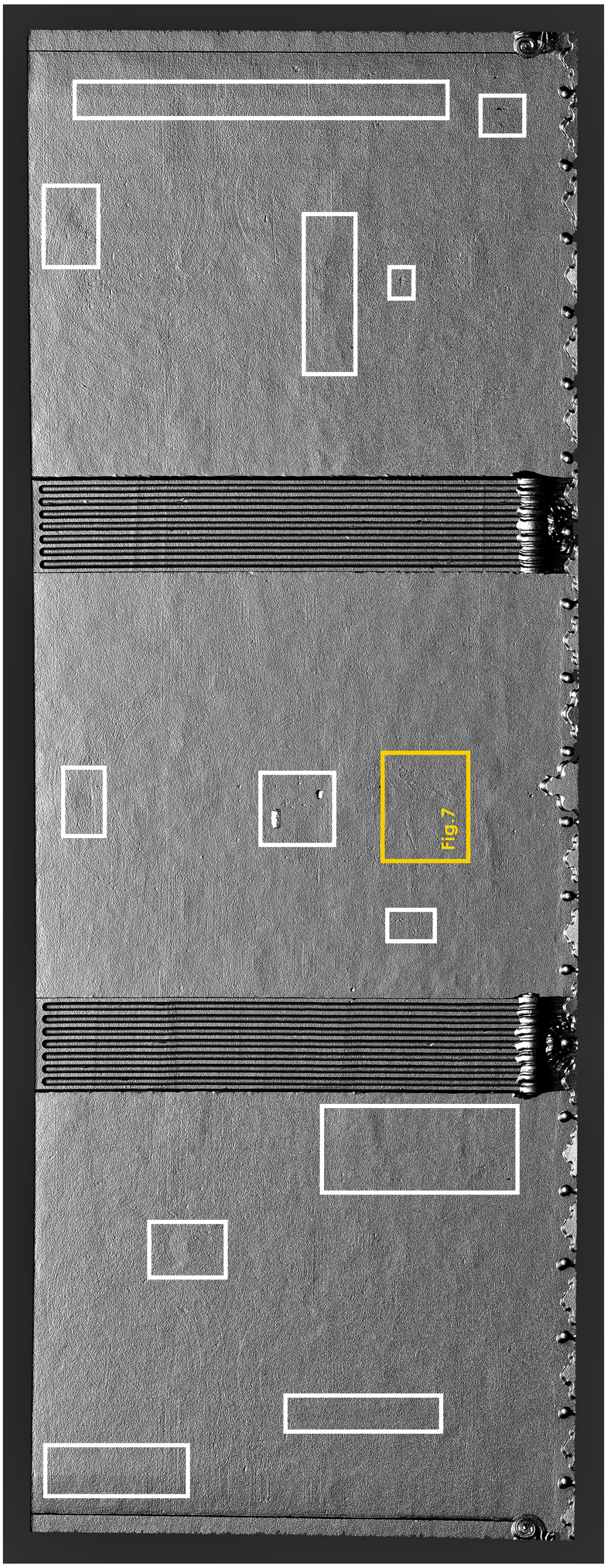

Figure 6. The V-RTI of the apse, as lit from above and after the unrolling. White frames refers to various surface features, such as engravings, scratches, and incisions. In yellow, the detail shown in Figure 7.

3. Comparison and Discussion

The data acquisition and the creation of the V-RTI make it possible to obtain valuable information for understanding the surface morphology and the overall conservation state of the artwork. The unrolling of the curved surface of the apse has enabled a comprehensive view of the support, on which areas of interest can be annotated for further investigation, either through direct observation or by means of additional non-invasive analyses.

Preliminary analysis in Figure 6—boxed in white—reveals various surface features attributable to different types of degradation. Raking light from above highlights specific marks that are likely the result of mechanical damage—such as scratches, missing areas, or irregular surface abrasions. These phenomena are observable across the entire surface of the artwork, yet remain relatively minor in nature, indicating a remarkably good state of preservation given the age of the support.

These traces may later be verified or refuted through the use of complementary diagnostic techniques, which can provide more precise and targeted analyses to supplement the information gathered during this phase of the study.

3.1 3D model optimization

The methodology adopted to optimize rendering times proved effective through a two-level strategy. On one hand, mesh decimation at a 1:350 ratio enabled the creation of an extremely lightweight model, easily manageable throughout all stages of the workflow. On the other hand, the generation and application of a NM—derived from the high-resolution model—to the simplified mesh preserved surface details. This approach proved particularly efficient, as it significantly reduced rendering times while maintaining a final visual quality comparable to that of the original high-resolution model [Figure 7].

Specifically, rendering the high-resolution model (approximately 50 million polygons) with a relatively high sampling value (128) required around 12 hours for completing the process, despite the use of a high-performance workstation. On the contrary, by reducing the mesh to 140,000 polygons, applying the NM, and adopting a minimal sampling value (1), the processing time was drastically reduced to approximately 5 minutes—while still yielding a result qualitatively comparable to that of the original model. These parameters—particularly the very low sampling value—allow for the generation of one image every 7 seconds, a significantly shorter time compared to the approximately 20 minutes required to achieve the same result using the high-resolution model. This makes the entire process more agile and feasible even on workstations with limited resources.

However, it is important to emphasize that the decimation ratio of 1:350 and the use of such a low sampling rate cannot be considered universally applicable parameters. In this specific case, the relative morphological simplicity of the artwork allowed for a significant reduction in polygon count without excessively compromising its surface features. In the presence of more complex geometries, however, such a level of decimation could result in the appearance of conspicuous artifacts or the loss of information that may be difficult to recover, even through the application of an NM.

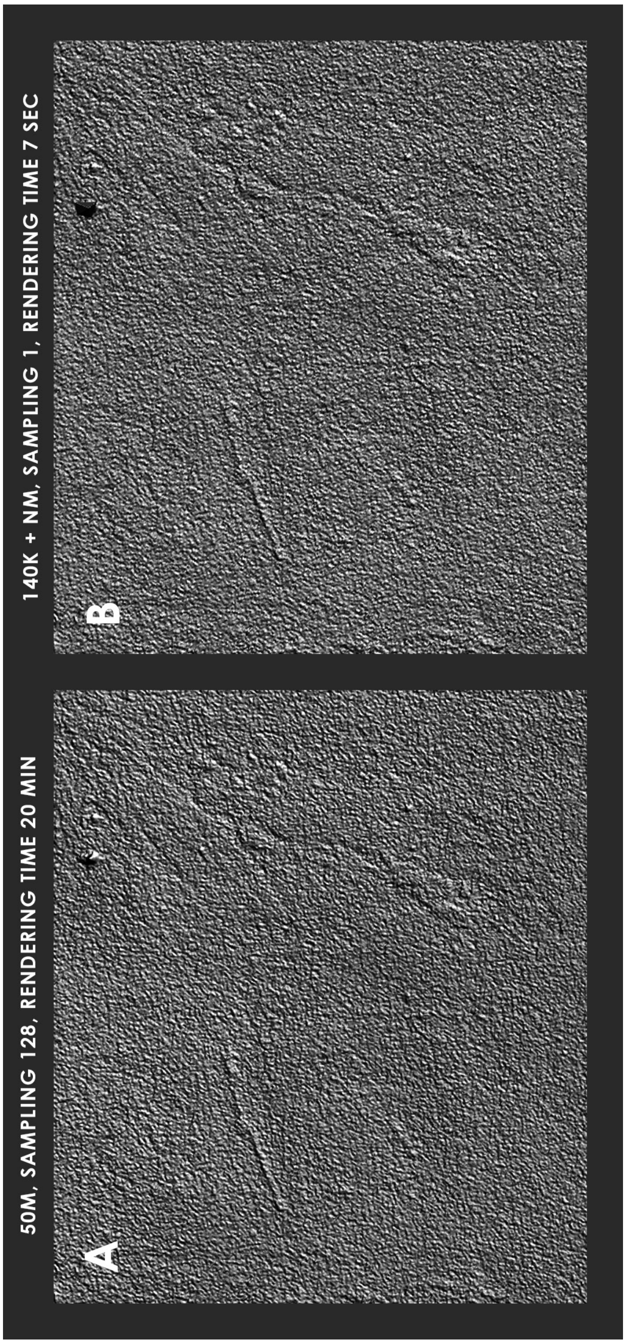

Figure 7. (A) Rendered image from the 50M polygons model with a sampling of 128; (B) Rendered image from the 140K polygons model with the high-res normal map and a sampling value of 1. The detail in (B) is comparable to (A). The significant difference lies in the rendering time, which is considerably lower for (B).

4. Conclusions

This study presents an integrated approach for the morphological analysis of surfaces in a complex scenario, including terrestrial laser scanner (TLS), planar development (unrolling), and Virtual Reflectance Transformation Imaging (V-RTI). The frescoed apse of the Church of Santa María del Temple in Valencia (Spain) served as an ideal testing ground for this methodology, demonstrating its effectiveness in contexts where traditional investigation techniques—such as conventional RTI—are not applicable due to spatial, logistical, or conservation constraints. The strength of this workflow lies in its rapid acquisition process, non-invasiveness, and the exclusive use of open-source softwares, ensuring both replicability and accessibility to a broad audience. V-RTI represents the first approach in reading the curved surface of the apse, and allows the identification of valuable details such as structural deformations that are not easily detectable from the ground-level viewpoint. The use of a normal map (NM) to transfer the complexity of the high-resolution mesh onto a simplified version significantly reduced rendering times, making the entire process compatible even with limited computational resources. Nevertheless, critical issues and limitations must be acknowledged. One of the main obstacles is related to the final resolution and colour accuracy of the V-RTI: since it is based on virtual renderings derived from TLS data, it cannot achieve the chromatic and detail richness obtainable by traditional RTI techniques based on real photographic images (Di Iorio et al., 2024), or by a 3D model generated through photogrammetry. While this method produces visually convincing results, it remains less effective in contexts where high-resolution optical information is essential.

In conclusion, the proposed workflow represents a robust and versatile solution for the preliminary analysis and documentation of complex surfaces, offering promising potential for both conservation and research projects.

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