Proposal of Radiometric Correction for the In-Situ Modelling of Polychrome Religious Carvings

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Keywords: Point Cloud, Texture, Geometry, 3D Scanner, Close-Range Photogrammetry.

Abstract

Digitalizing cultural heritage demands accurate 3D models for documentation, conservation, and restoration, focusing on both geometry and texture. For medium-sized objects, 3D scanning commonly provides accurate geometry, while photogrammetry excels at capturing texture. Therefore, a hybrid workflow is often used. However, on-site acquisition of complex objects, such as the polychrome 'Saint Catherine of Alexandria' sculpture in Jaén, Spain, presents significant radiometric challenges due to variable lighting and shiny surfaces. This study details a two-phase methodology to create a photorealistic 3D model of this carving. The first phase involved capturing geometry with a structured light scanner and acquiring photogrammetric images using a conventional camera. These datasets were then fused, combining the 3D scan and oriented photogrammetric block to obtain the initial 3D model. Additionally, a colorimeter simultaneously measured true colour values of seven distinct chromatic segments (e.g., gold tunic, face, shoes) to address the carving's challenging reflectivity. The second phase focused on radiometric correction. Images were segmented using a divided 3D mesh and depth maps generated for each segment. Each segment's RGB values were then adjusted to match the colorimeter's average reference value for that specific segment. This zonal correction strategy ensured colour homogeneity. The resulting 3D model, textured with these corrected images, showed a significant improvement in colour realism. The average RGB distance between colorimeter measurements and the model's texture was substantially reduced using this approach. This preliminary study demonstrates the potential and robustness of this method for achieving accurate colour fidelity in 3D models, even under challenging on-site conditions.

1. Introduction

The digitalization of cultural heritage, using accurate and reliable models, is an essential tool for its documentation, conservation, and dissemination. To obtain high-quality models, various methods and techniques are employed, primarily photogrammetry and 3D scanning systems. Generally, 3D scanners are designed for the precise acquisition of an object's geometry. Although some systems incorporate cameras, the quality of the captured images is often insufficient to produce realistic, high-quality textures. Photogrammetric techniques, on the other hand, while sometimes presenting greater difficulties for geometric acquisition, offer superior potential for capturing the object's true texture. For this reason, a hybrid workflow is often adopted, combining the strengths of both approaches to achieve optimal results for both the geometry and texture of the digitized object (Alshawabkeh et al., 2021; Pérez-García et al., 2024). However, the selection of the technique will always depend on the characteristics of the scene or object, the desired product type, resolution and quality requirements, and the acquisition environment.

For medium-sized objects, such as sculptures, 3D documentation techniques primarily rely on structured light scanning (SLS) (Akca, 2012; Cui et al., 2021; Kęsik, 2022), terrestrial laser scanning (TLS), and close-range photogrammetry (CRP). Various authors have compared these techniques (Adamopoulos et al., 2021; Barszcz et al., 2021; Melendreras et al., 2021). Generally, the most suitable technique is determined by the object's type and characteristics, as well as environmental conditions. In this context, Melendreras et al. (2021) identified structured light scanners as offering the highest geometric and colorimetric quality for religious imagery. Other studies have integrated different techniques: Shao et al. (2019) combined TLS and SLS, while García-Molina et al. (2021) used SLS for geometry and CRP for texture, and Colomo et al. (2016) utilized TLS for geometry and CRP for texture.

However, in many cases, the scenes where these techniques must be applied are far from the ideal laboratory conditions, where lighting and auxiliary equipment are adequate and controllable. An example is the acquisition process described in Ferdani et al. (2024), where the object is placed inside a light box. This setup minimizes shadows, reflections, and ambient light pollution, speeds up image capture, ensures a constant and controlled shooting distance to the object, and facilitates its scaling through the placement of control marks. In situations where the object cannot be moved to a laboratory and data acquisition must be carried out on-site, significant challenges can arise (Kęsik et al., 2022), particularly concerning image capture. These cases include both outdoor and indoor scenes, such as museums, churches, etc. Such challenges are related to the characteristics of the environment (non-uniform lighting, lack of space for photography, non-uniform background texture) or the object itself (presence of shiny or excessively dark surfaces, lack of texture on certain parts of the object, etc.) (Williams et al., 2024). In these scenarios, ensuring accurate modelling and colour fidelity when texturing the model can be a considerable challenge.

Various approaches have been developed to enhance the radiometry of 3D models based on photogrammetry, or to facilitate the photogrammetric process and obtain better 3D models. These techniques are based on image enhancement, involving the modification of one or more image attributes

(Maini and Aggarwal, 2010). The process ranges from simple image enhancements based on histogram adjustments (e.g., stretching, equalizing, adaptive equalizing, and exact matching) (Łabędź et al., 2021), colour balancing, image denoising, colour-to-grayscale conversion, and image content enrichment (Gaiani et al., 2016), the use of polarized filters and High Dynamic Range imaging (HDR) (Guidi et al., 2014), to more sophisticated methods based on machine learning (Anoop and Deivanathan, 2024). A more detailed review of these methods can be found in Wang et al. (2020). In this regard, one method used for colour measurement is the employment of colour charts (Barbero-Alvarez et al., 2023). These allow for the application of correction algorithms to images before photogrammetric reconstruction, aiming to correct the colour bias introduced by acquisition conditions and to approximate the final colours to the objects' 'true colours.' Other tools used for colour measurement are spectrophotometers and colorimeters. Spectrophotometers provide a spectral response of colour to light stimulation, translated into physical coordinates of the colour space. Colorimeters, on the other hand, offer a direct conversion into CMYK, RGB, and L*a*b* colour spaces, which represent perceptual colour (Valge et al., 2022). While both devices allow for fast and accurate colour determination, Valge et al. (2022) concluded that spectrophotometers can be more expensive compared to colorimeters.

Figure 1. Saint Catherine of Alexandria: a) views of the carving; b) usual location of the carving in a chapel within St. Catherine Castle in Jaén (Spain).

1.1 St. Catherine of Alexandria carving

The object documented in this study is the sculpture of Saint Catherine of Alexandria (Figure 1a), a Neo-Baroque polychrome wooden sculpture, 1.55 m high, dated 1942, and created by José María Ponsoda. The sculpture is typically housed inside an approximately 10 m² chapel located in one of the towers of the Castle of Santa Catalina in Jaén, Spain (Figure 1b). However, the image is frequently moved to other places for worship, and every year on November 25, it is taken outside in a procession. During these activities, the sculpture has suffered minor impacts and the effects of inclement weather such as sun or rain, which have affected its condition. Chromatically, several segments can be distinguished in the carving, with a predominance of gold and silver tones in the clothing (tunic, cape, and shoes), as well as in the face, hands, and hair. The polychrome finish has a glossy appearance (Figure 1a). As a result, the polychrome presents numerous reflective surfaces, which makes it difficult to acquire the image's texture due to undesirable reflections that vary based on the geometry between the camera, object, and environment. The image is characterized by a high level of detail in the tunic, with numerous folds that complicate the graphic documentation of its geometry (Figure 1a). A restoration process began in 2025, for which initial documentation of its pre-restoration state was conducted. This study describes the results of this preliminary documentation, focusing on aspects related to its geometry and radiometry. The documentation was performed inside the chapel, which posed a considerable challenge due to the limited space and illumination conditions of the scene. In this sense, we propose a radiometric correction to adjust the model's texture to reality, avoiding undesirable effects caused by suboptimal illumination and shiny surfaces.

1.2 Objectives

This study presents the preliminary work for the on-site acquisition of a photorealistic model of a religious carving, using photogrammetry and 3D scanning techniques. The main objective is to address radiometric issues caused by the environment and the object itself through the radiometric correction of the captured images, aiming to preserve their true colours.

The structure of this document is as follows: First, we describe the methodology and its application for documenting the religious carving of St. Catherine of Alexandria, considering a radiometric correction to remove undesirable effects caused by the environment and the sculpture itself. Second, the primary results obtained in this study are summarized, followed by a discussion. Finally, the main conclusions of the study are presented.

2. Methodology and application

The proposed methodology (Figure 2) is divided into two main phases. The first phase involves the capture and initial processing of data from a 3D scanner (SLS), photogrammetry (CRP), and a colorimeter. The second phase focuses on the radiometric correction of the photogrammetric images based on the colorimeter measurements, leading to the final 3D model.

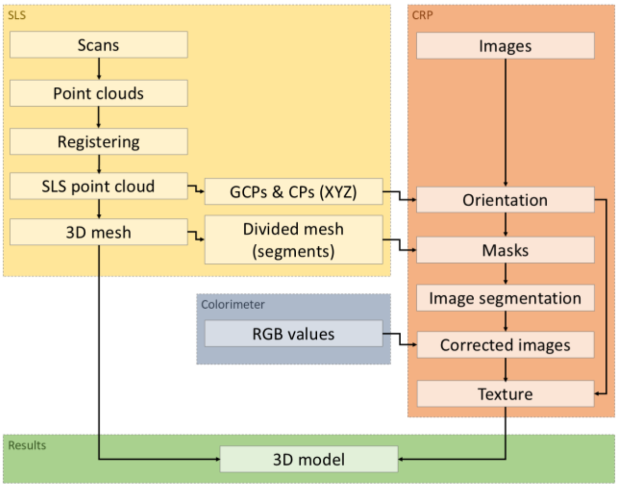

Figure 2. Methodology developed in this study.

Figure 3. Data acquisition: a) SLS: EinScan Pro 2X; b) CRP: Sony Alpha 6100; c) colorimeter: NCS Colourpin-Pro.

2.1 Data acquisition

In the first phase, the geometry was captured using an EinScan Pro 2X structured light 3D scanner (Figure 3a). Due to the carving's size, six scans with overlapping areas were performed. The scanning mode avoided the use of targets, so point cloud registration was carried out using the ICP algorithm (Huang et al., 2021) (Figure 4).

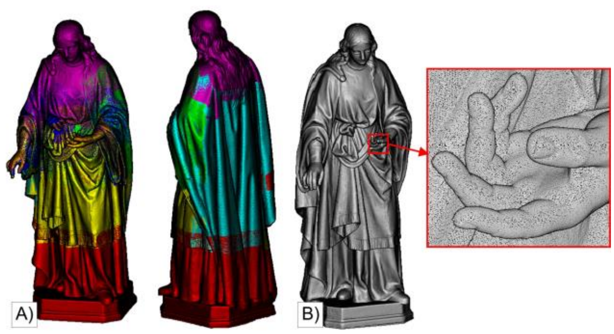

Figure 4. SLS point cloud: a) registering of six point clouds; b) detailed view of the final point cloud.

For photogrammetry (CRP), a Sony Alpha 6100 camera with a 30mm lens was used. Image capture followed a convergent ring pattern around the object at a distance of less than 1 meter (Figure 3b), adhering to CIPA recommendations (Waldhäusl et al., 2013). Approximately 600 photographs were acquired. However, due to the carving's characteristics and the challenging environment previously described, the images exhibited significant radiometric issues. Specifically, the same areas of the object showed considerable radiometric variability depending on the camera's position. For instance, Figure 5 illustrates different photographs of the same area taken from various viewpoints, revealing distinct histograms and varying RGB values for specific points. The glossy polychrome finish resulted in extensive reflections that hindered the capture of true colours. To mitigate these reflections, we minimized external light sources by closing the chapel's doors and windows, and employed diffuse artificial illumination. Furthermore, to address this challenge, colour measurements of the carving's different chromatic segments were simultaneously taken during image acquisition using an NCS Colourpin-Pro colorimeter (Figure 3c).

2.2 Data fusion

Once data capture was completed, data fusion was performed in two steps. First, all SLS point clouds were registered using EXScan Pro software, generating a point cloud with homogeneous resolution after applying semi-automatic cleaning and filtering. From this combined point cloud, comprising approximately 23 million points, a 3D mesh was generated, consisting of 46 million triangles. Next, a set of well-distributed control points (GCPs, see Figure 2) were extracted from the point cloud and measured in the images for photogrammetric orientation. These points were carefully selected from clearly identifiable details present in the images. Finally, this orientation was carried out using these control points within Agisoft Metashape software. The outputs of this phase include a merged 3D mesh and the oriented photogrammetric block.

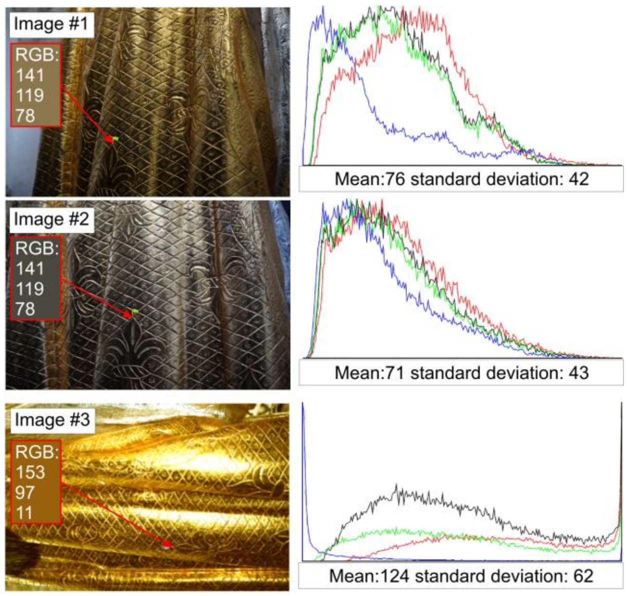

Figure 5. Example of radiometric differences between three images of the same area depending on the camera location.

2.3 Radiometric correction

The second phase focuses on the radiometric correction of the images and the subsequent texturing of the 3D model using these corrected images. The radiometric correction process aimed to align the image colours with the reference values measured by the colorimeter for each identified chromatic segment. A global correction could potentially improve some areas while degrading others; therefore, we implemented zonal transformations based on specific segments. Seven distinct segments were defined (cape, hair, face and hands, silver tunic, gold tunic, sleeve, and shoes), and the 3D mesh was manually divided accordingly into these seven parts (Figure 6a). This segmentation was performed using Agisoft Metashape software.

For each segment within the oriented photogrammetric block, depth maps were calculated for every image. For instance, if an image (e.g., Figure 6b) contained six parts (cape, hair, face and hands, silver tunic, gold tunic and sleeve), six corresponding depth maps were generated for that image. Segmentation was then achieved by creating masks derived from these depth maps for each image (Figure 6c). It is important to note that a single pixel might be associated with multiple depth values (e.g., a hand in front of a tunic); in such cases, the lowest depth value was considered. These calculations were performed using the Python API of Agisoft Metashape software.

Once all images were segmented, they were corrected segment by segment using a reference RGB value acquired with the colorimeter. These seven reference RGB values (one for each part of the carving) were obtained as average values from multiple colorimeter measurements for each segment. Standard deviations of these multiple measurements from the colorimeter were approximately 6 digital levels. For each segment in an image, we adjusted that specific area to match its predetermined reference RGB value. This procedure ensured consistent RGB values for each segment across all images where it appeared. After this image correction process, a refined texture was generated and subsequently applied to the 3D mesh to create the final 3D model. The radiometry of the final model was further validated through a comparison with the average values obtained directly from the colorimeter.

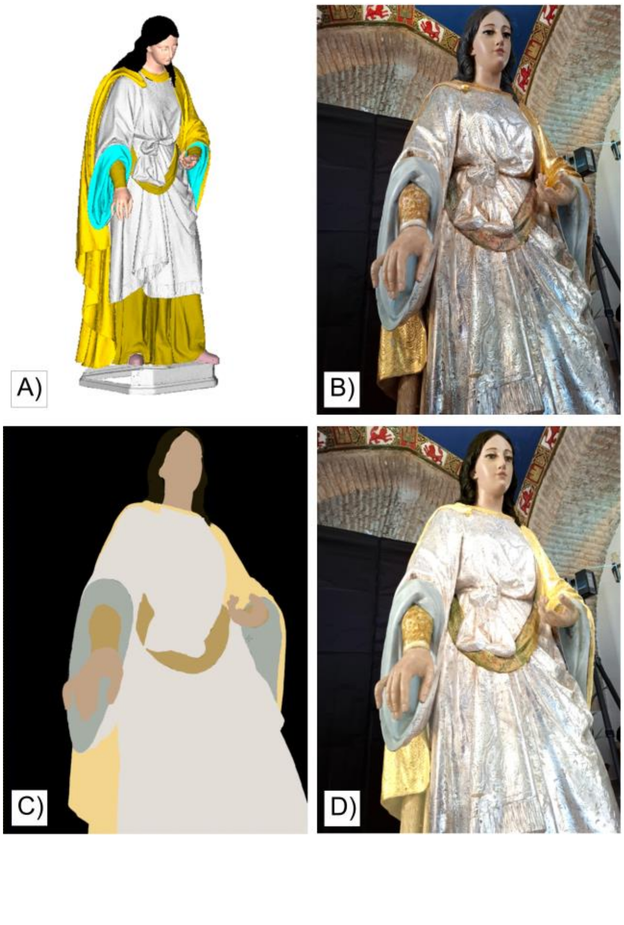

Figure 6. Example of radiometric correction procedure: a) 3D mesh with segments; b) original image; c) segments based on depth maps; d) corrected image.

3. Results and discussion

A 3D model with a resolution of 0.2 mm was generated from the dense point cloud (approximately 23 million points) and subsequently textured using the radiometrically corrected images (approximately 600 images). The benefits of the proposed approach were analysed by comparing the resulting 3D models with and without radiometric correction (Figure 7).

The advantages of employing radiometrically corrected images for texturing are evident through visual inspection. Figure 8 presents two comparative examples of original images versus corrected images for the cape and silver tunic segments, alongside their colorimeter-defined average true colours. A clear radiometric improvement is visually apparent, with the corrected images closely resembling the true colours measured by the colorimeter. Notably, undesirable effects caused by reflections have been significantly minimized. For instance, in the lower part of the cape (Figure 8a), the reflection from the red floor, prominent in the original image, is largely mitigated in the corrected version. Similarly, in Figure 8b the glossy surfaces visible in certain areas of the silver tunic in the original images are effectively removed in their corrected counterparts.

Figure 7. 3D models obtained in this study: a) without radiometric correction; b) with radiometric correction.

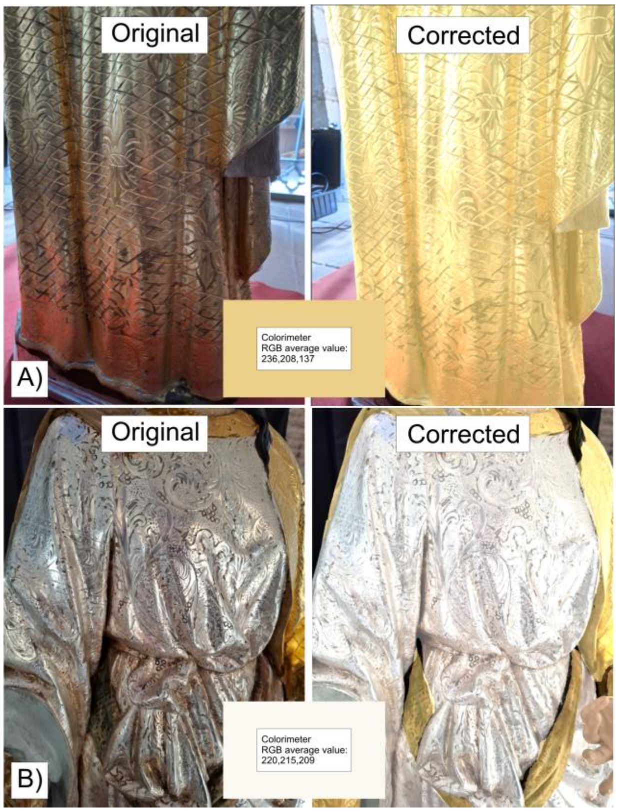

Figure 8. Comparison of original vs. corrected images and colorimeter RGB average value: a) cape; b) silver tunic.

Furthermore, Figure 9 graphically illustrates the correlation between the average RGB value of all images for each segment and the colorimeter's average value for that segment (representing the true colour). Figure 9a highlights the challenges of applying a global radiometric correction, as it fails to uniformly improve all image segments. In contrast, comparing the correlation for original images (Figure 9a) versus corrected images (Figure 9b) clearly demonstrates the significantly better alignment of the corrected images with the true colours, a stark improvement over the poor fit observed in the originals. Additionally, this radiometric correction process also led to a noticeable contrast enhancement, as further depicted in Figure 9.

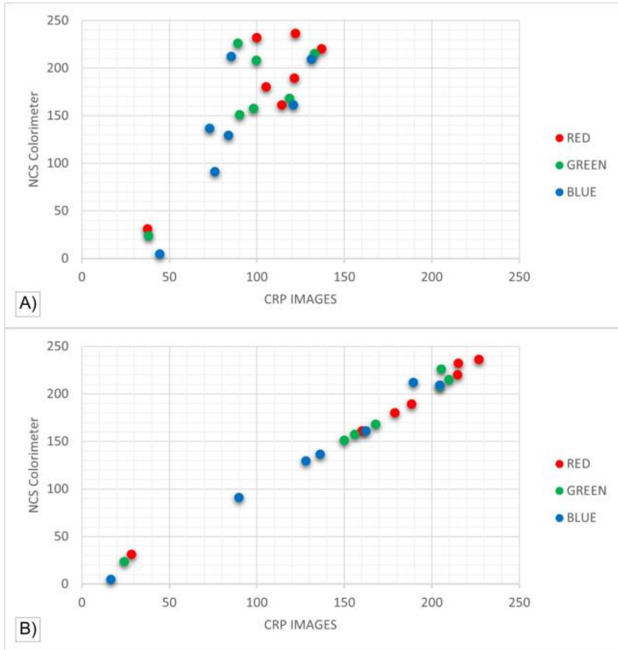

Figure 9. Comparison (digital levels by channel) between images and the colorimeter average value by segments: a) original images; b) corrected images.

The analysis presented in Figure 9 indicates that the radiometric enhancement process effectively yields corrected RGB values closely resembling the true measurements obtained from the colorimeter across the images. Complementing this visual and graphical analysis, a quantitative point-based analysis was performed on the textured models. For this, the points corresponding to the colorimeter measurements were identified in both the original and radiometrically corrected texture models for each colour segment. Table 1 summarizes the results, revealing a significant reduction in the average RGB distance (in digital levels) between the colorimeter's true colour and the model's textured colour. Specifically, the average distance decreased from 75 digital levels ($\sigma = 23$) for the colorimeter vs. original texture to just 26 digital levels ($\sigma = 14$) for the colorimeter vs. corrected texture. This demonstrates a remarkable improvement of approximately 65.3% in colour accuracy when radiometric correction was applied. It's important to note that these results reflect an enhancement beyond any automatic radiometric adjustment performed by Agisoft Metashape software.

Segment	RGB distance	
	Original	Corrected
Cape	125	22
Face and hands	60	18
Sleeve	62	25
Hair	72	10
Gold tunic	65	29
Silver tunic	58	26
Shoes	75	54
Average value	75	26

Table 1. RGB distance (in digital levels) between colorimeter measurements and texture models (original vs. corrected) for each segmented area.

4. Conclusions

This study successfully demonstrates a robust methodology for generating high-fidelity, photorealistic 3D models of cultural heritage objects, particularly challenging ones like the polychrome 'Saint Catherine of Alexandria' sculpture. Our hybrid approach, which combines structured light scanning for accurate geometry with photogrammetry for detailed texture, effectively addresses the complexities of on-site data acquisition in non-ideal environmental conditions. The potential of this study lies in fusing these techniques to leverage their individual strengths, thereby achieving high-quality textured models and developing a methodology capable of making the texturing genuinely resemble reality by homogenizing colours across all images. This is crucial, especially when the environment or the object itself doesn't allow for optimal working conditions.

The inability to move the sculpture to a laboratory with environment-controlled conditions, coupled with the polychrome's inherent characteristics, posed significant challenges for both data acquisition and processing. For instance, the structured light scanner used is sensitive to lighting conditions and object colours; it performs best with natural illumination and light, matte colours (Williams et al., 2024). However, our study object displayed a full range of colours (e.g., dark hair) and was almost entirely covered in shiny surfaces (e.g., gold, silver). Additionally, variations in ambient light within the study area further complicated data capture. Similarly, photographic capture and processing presented comparable problems, alongside other issues related to radiometric quality essential for texturing. Obtaining a photorealistic texture with RGB values closely matching the carving's true colours necessitated a radiometric correction. However, the commonly used colour card approach was largely unfeasible due to the varying lighting, shooting distances, and brightness across individual images.

A key contribution of this research in this context is the application of a novel radiometric correction strategy based on zonal transformations. By leveraging manual measurements of true colour using a colorimeter on different chromatic segments of the carving, we effectively overcame the significant problems posed by variable lighting and highly reflective object surfaces. Quantitative analysis unequivocally corroborates the effectiveness of this approach, showing a remarkable 65.3% improvement in colour accuracy. The average RGB distance between the measured true colours and the model's texture was substantially reduced from 75 to just 26 digital levels, demonstrating a significant improvement beyond any automatic software adjustment.

This preliminary work highlights the immense potential of integrating systematic colour measurement into hybrid 3D documentation workflows. The proposed method not only provides visually realistic models but also ensures high colour fidelity, which is crucial for accurate documentation, conservation monitoring, and dissemination of cultural heritage. Working with zonal segments, rather than global image processing, has allowed us to homogenize images that were radiometrically very distinct due to variable lighting conditions and the relative position of the camera to the object and light source. Future work will explore the possibility of automating segment identification and testing the methodology on a wider range of challenging cultural heritage objects.

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