Fast acquisition for modelling heritage-related complex scenes based on TLS and spherical photogrammetry

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Abstract

The 3D documentation of complex scenes—characterized by restricted spaces, irregular geometries, and poor lighting—remains a significant challenge in cultural heritage. This study proposes a rapid data acquisition methodology based on the multi-sensor fusion of Terrestrial Laser Scanning (TLS) and Spherical Photogrammetry (SP). The approach was validated in two distinct complex environments: an ancient Egyptian rock-cut tomb (QH36, Aswan, Egypt) and a natural Iberian sanctuary cave (Cueva de la Lobera, Jaén, Spain). The methodology uses TLS to establish a high-precision geometric backbone, achieving registration errors below 0.5 cm. By extracting Ground Control Points (GCPs) directly from the TLS point cloud, the reliance on traditional total station surveying was significantly reduced, enhancing fieldwork efficiency. SP was implemented to obtain realistic textures and to support geometry by using a 360-degree multi-camera with integrated LED lighting, providing full spherical coverage and high-resolution textures. Results indicate that SP is at least six times faster than conventional photogrammetry. Furthermore, the use of TLS-derived meshes enabled advanced digital masking to remove non-interest objects (e.g., archaeological equipment) from the final models. While conventional photogrammetry remains the benchmark for fine architectural details, this research demonstrates that the TLS-SP fusion is the most viable solution for the rapid, high-accuracy documentation of constrained heritage sites. This hybrid workflow ensures geometric integrity while drastically reducing acquisition times, providing a robust framework for future archaeological and conservation projects.

1. Introduction

The graphical documentation of cultural heritage has undergone a profound transformation over the last few decades, driven by the rapid evolution of geomatic techniques, sensors, and processing algorithms (Remondino, 2011). Traditionally used for conservation and dissemination, these digital models now serve as the foundation for structural analysis, stratigraphic studies, and Heritage Building Information Modeling (HBIM) (Murphy et al., 2009; Lovell et al., 2023). However, the documentation of "narrow scenes"—defined by challenging geometrical characteristics, limited accessibility, and restricted space—remains a significant challenge (Lerma et al., 2010; Pérez-García et al., 2024). Beyond these physical difficulties, modeling heritage sites often requires rapid data acquisition due to factors ranging from cost reduction and site accessibility to concurrent activities (e.g., archaeological excavations, tourism) or strict time constraints. These conditions necessitate a reduction in capture time while maintaining a high level of geometric and radiometric quality—a requirement that is often at odds with the increased data density needed to ensure full coverage in such environments.

In these contexts, standard data acquisition procedures often prove inefficient due to extreme sensor-to-object proximity, poor lighting, or frequent occlusions. To overcome the limitations of individual sensors, modern workflows emphasize multi-sensor data fusion (Guidi et al., 2009; Alshawabkeh et al., 2021; Samadzadegan et al., 2025). Terrestrial Laser Scanning (TLS) is widely regarded as the benchmark for geometric accuracy, providing dense point clouds in minutes. Nevertheless, in complex interiors such as burial chambers or caves, relying solely on TLS can be costly and time-consuming due to the high number of scanning stations required to avoid data gaps. Conversely, Close-Range Photogrammetry (CRP) offers superior radiometric quality and the flexibility to reach inaccessible areas in complex scenes using telescopic masts (Pérez-García et al., 2019).

The integration of these techniques allows for a balanced approach: TLS provides a stable geometric framework, while photogrammetry contributes high-resolution textures and fills gaps in occluded zones. Recent studies have even demonstrated the feasibility of using TLS point clouds to extract coordinates for Ground Control Points (GCPs), significantly reducing the time spent on traditional surveying with total stations. A major area of innovation in documenting narrow scenes is the use of 360-degree cameras and fisheye lenses (Fangi, 2007), a field defined as spherical photogrammetry (SP) (Fangi, 2009). These sensors offer an ultra-wide Field of View (FoV), which significantly minimizes the number of captures required for full scene coverage compared to conventional pinhole cameras; furthermore, they are often characterized as cost-effective solutions (Herban et al., 2022). The practical application of SP in cultural heritage has been extensively validated through various landmark studies. Fangi (2007; 2009) pioneered multi-image spherical photogrammetry for documenting large-scale monuments, demonstrating significant reductions in fieldwork time and image count. Fangi and Nardinocchi (2013) analysed the photogrammetric use of spherical or panoramic images. Building on this, Barazzetti et al. (2018) further explored the geometric potential of omnidirectional sensors, proving that 360-degree cameras are particularly effective for capturing holistic data in complex indoor environments and confined spaces. These studies underscore the transition toward more agile, yet comprehensive, documentation workflows. Such methodologies have been applied to complex heritage scenes such as spiral staircases (Perfetti et al., 2017), caves (Alessandri et al., 2019), and tombs (Skarlatos et al., 2024). Building upon these foundations, research conducted by

Pérez-García et al. (2024) has highlighted the differences between using original fisheye images and synthetic spherical or panoramic images. While the panoramic images simplify the orientation process, they are prone to geometric errors introduced during the "stitching" process. Advanced stitching techniques based on depth maps have shown superior accuracy compared to standard feature-based methods, yet original fisheye images remain the most geometrically reliable option for high-precision modeling. Furthermore, the emergence of 360-degree videogrammetry offers even greater capture efficiency, though it often faces challenges such as motion blur and lower resolution (Barazzetti et al., 2017), especially within interior environments (Gómez-López et al., 2025).

For extremely complex or large-scale interiors, Mobile Mapping Systems (MMS) based on Simultaneous Localization and Mapping (SLAM) algorithms have been introduced (Shi et al., 2012; Ji et al., 2020; Zhang and Huang, 2021). These handheld or wearable systems allow for real-time data capture while the operator moves through the scene. While MMS can significantly accelerate the documentation of narrow scenes, some issues must be considered, such as lower resolution, noise levels, and drift effects (Elhashash et al., 2022). Consequently, the resulting point clouds may show lower accuracy than those from static TLS, making them more suitable for preliminary documentation (Bonora and Colapietro, 2026) and HBIM applications.

Despite these advancements, there is a clear need to refine workflows that balance acquisition efficiency with geometric accuracy in the most restrictive environments. This research builds upon these evolving methodologies, proposes a methodology for fast data acquisition, analyzing the effectiveness of multi-sensor fusion of TLS and SP data to provide a robust framework for the 3D documentation of complex heritage scenes, ranging from natural features to human-made structures. This methodology is applied to two case studies characterized by narrow scenes: an artificially excavated tomb and a natural cave. While both share common features, they also present specific differences of interest for this study, particularly the contrast in surface types and lighting conditions. These aspects pose a significant challenge for the methodology developed herein.

1.1 Case study 1: Egyptian tomb

The first case study focuses on the documentation of an Egyptian rock-cut tomb, specifically the QH36 tomb located in the necropolis of Qubbet el-Hawa (Aswan, Egypt). This burial structure dates back to the Middle Kingdom period and was built for Sarenput I, who served as nomarch of the First Nome of Upper Egypt during the early Twelfth Dynasty, likely under the reign of Senusret I (1971–1926 BCE). The structure of approximately 110 m^2 (public area) is composed of multiple chambers, vertical shafts, and narrow scenes with significant occlusions, making it a highly complex environment to model. In this instance, the presence of concurrent archaeological work and tourists necessitated rapid data acquisition. Furthermore, excavation tasks were carried out over several field seasons, with each campaign focusing on individual or multiple structures. The tomb is occupied by various archaeological materials and equipment, such as crates of cataloged pottery, which present additional challenges for data acquisition and complete scene coverage. Due to logistical constraints, these materials cannot be removed from the tomb and can only be displaced within the scene, requiring adaptive capture strategies.

1.2 Case study 2: Cave

The second case study involves a natural cave used by ancient Iberians as a sanctuary (4th–3rd centuries BCE): the Cueva de la Lobera in Castellar (Jaén, Spain). This site served as a spiritual center where thousands of bronze figurines (ex-votos) were offered to the deities. The structure consists of a narrow entrance and a main chamber of approximately 30 m^2 characterized by a complex geometry with irregular rock surfaces, discontinuous formations, and sediment deposits. In this case, data acquisition was strictly limited to a single day due to access permits and logistical constraints.

1.3 Objectives

The primary objective of this study is to develop a methodology for generating 3D models of narrow scenes, prioritizing rapid data acquisition while ensuring high geometric and radiometric quality through data fusion. As a secondary objective, this research seeks to identify site-specific challenges and potential methodological improvements by considering the unique characteristics of both environments under study.

2. Methodology

This study proposes a methodology (Figure 1) for the fast acquisition of narrow scenes based on the data fusion of two geomatic techniques: Terrestrial Laser Scanning and Spherical Photogrammetry. TLS provides high-density point cloud acquisition and enables automated registration by maintaining large overlaps between adjacent scans. Meanwhile, SP facilitates the acquisition of point clouds and high-resolution textures, significantly improving field efficiency compared to conventional photogrammetry due to its ultra-wide FoV. In this approach, TLS is utilized to establish the scene’s core geometry and to extract the coordinates of several Ground Control Points (GCPs) for georeferencing SP products, as well as Checkpoints (CPs) to assess their positional accuracy. Conversely, SP provides a realistic radiometric texture and a secondary point cloud to supplement TLS data in areas affected by occlusions or gaps.

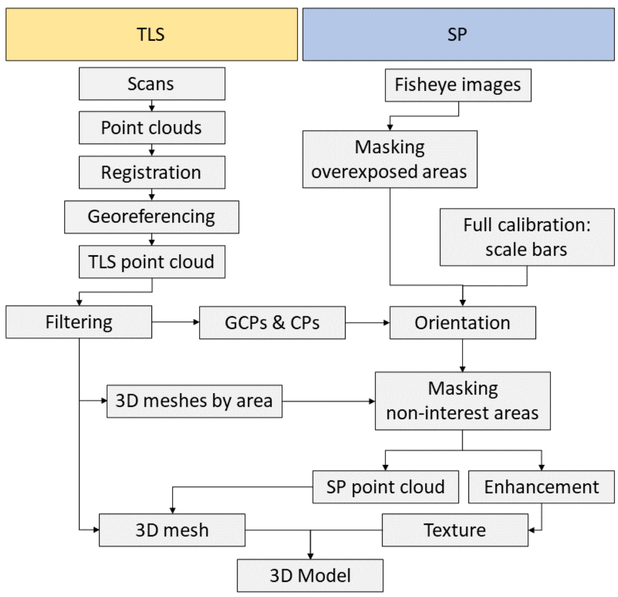

Figure 1. Methodology proposed in this study.

2.1 Terrestrial Laser Scanning (TLS)

The methodology employs a static laser scanning device (e.g., Faro Focus x130), which allows for extensive coverage from each station and fast acquisition while ensuring geometric precision. The Faro Focus x130, for instance, offers a FoV of 300° vertical and 360° horizontal, performing scans in approximately 5 minutes with a density of 7 mm at 10 m and a ranging accuracy of approximately 2 mm. The procedure begins with the strategic selection of scan stations to minimize occlusions and guarantee substantial overlaps between adjacent point clouds, facilitating automatic registration. Data acquisition is performed without the color measurement mode to maximize field efficiency and reduce capture time. Point cloud registration is based on the Iterative Closest Point (ICP) algorithm (Besl and McKay, 1992), resulting in a comprehensive point cloud referred to a local Coordinate Reference System (CRS). To georeference this data to a global CRS, a rigid 3D transformation is applied using several well-distributed GCPs. These points are materialized with targets located at the entrance of the scene, measured via traditional surveying (e.g., total station or GNSS in outdoor areas). By using the TLS point cloud as the primary geometric reference, the number of external GCPs can be minimized to at least three, further improving efficiency. Following georeferencing, a filtering procedure is applied to remove points related to undesirable objects (e.g., noise, archaeological tools or storage boxes). In cases where objects cannot be removed, multiple scans are performed before and after shifting them within the scene to ensure the cleanest possible dataset. Furthermore, the point cloud is subsampled to achieve a homogeneous spatial distribution with a minimum point spacing of 1 cm. This filtered TLS point cloud serves as the basis for the final 3D mesh and provides the source for the GCPs and CPs used in the SP orientation phase.

2.2 Spherical Photogrammetry (SP)

SP utilizes a 360-degree multi-camera, composed of multiple sensors and fisheye lenses that provide full spherical coverage. Acquisition involves a high density of shot stations distributed along the scene. To handle immovable archaeological materials outside the scene, image acquisition is repeated before and after moving such objects a certain distance, allowing for subsequent masking of unwanted elements. A significant challenge in interior environments is lighting, which directly impacts radiometric quality. Our approach incorporates a 360-degree LED-based lighting system mounted on the camera, providing diffuse illumination within a 2–3 meter range. However, this setup results in overexposed areas in the upper zones of the fisheye images where the light source is visible. To mitigate this, specific masks are applied to all images prior to the orientation process. The internal geometry of the multi-camera sensors is defined through a full calibration of intrinsic and extrinsic parameters. These constraints—such as the fixed distance between sensors—are applied during the image orientation process to enhance stability, using tools such as scale bars in Agisoft Metashape v2 (Pérez-García et al., 2024). The orientation follows the Structure from Motion (SfM) algorithm (Ullman, 1979; Lowe, 2004). Once oriented, the preliminary 3D meshes derived from the TLS are used to project masks onto the SP images, effectively excluding transient objects from the final reconstruction. The final stage involves generating the SP point cloud using Multi-View Stereo (MVS) algorithms (Seitz et al., 2006; Furukawa and Hernández, 2015). This point cloud supplements the TLS data, filling any remaining gaps to produce a continuous 3D mesh. Finally, the images undergo a contrast enhancement process to improve radiometry. The resulting optimized texture is projected onto the 3D mesh, yielding the definitive, high-resolution 3D model of the heritage scene.

3. Application and Results

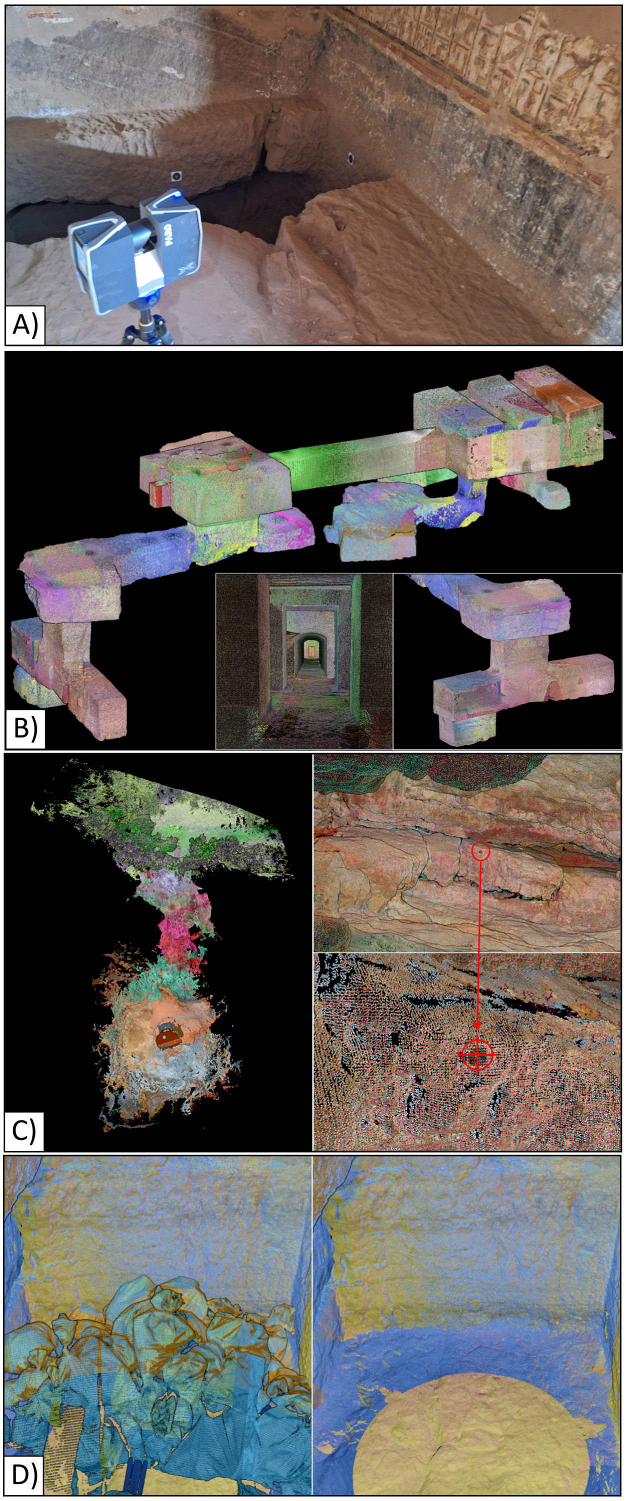

Figure 2. TLS data acquisition and processing: a) QH36 data acquisition; b) views of the registered QH36 point cloud; c) Registered point cloud of the natural cave with a detailed view of target measurement; d) Visualization of the point cloud filtering process (pre- and post-cleaning).

The application of the proposed methodology to both case studies revealed significant similarities, as well as distinct differences arising from site-specific characteristics and the temporal constraints of data acquisition. In the QH36 tomb, acquisition was conducted over several campaigns, synchronized with the phases of archaeological excavation. Consequently, the capture strategy required substantial overlap between campaigns to ensure a seamless final model. Furthermore, field work had to be highly efficient to minimize interference with tourists and ongoing archaeological tasks. In contrast, the natural cave was surveyed in a single day without the possibility of re-visitation. Both environments presented significant challenges, including poor lighting, frequent occlusions, and, specifically in the cave, high dust concentrations.

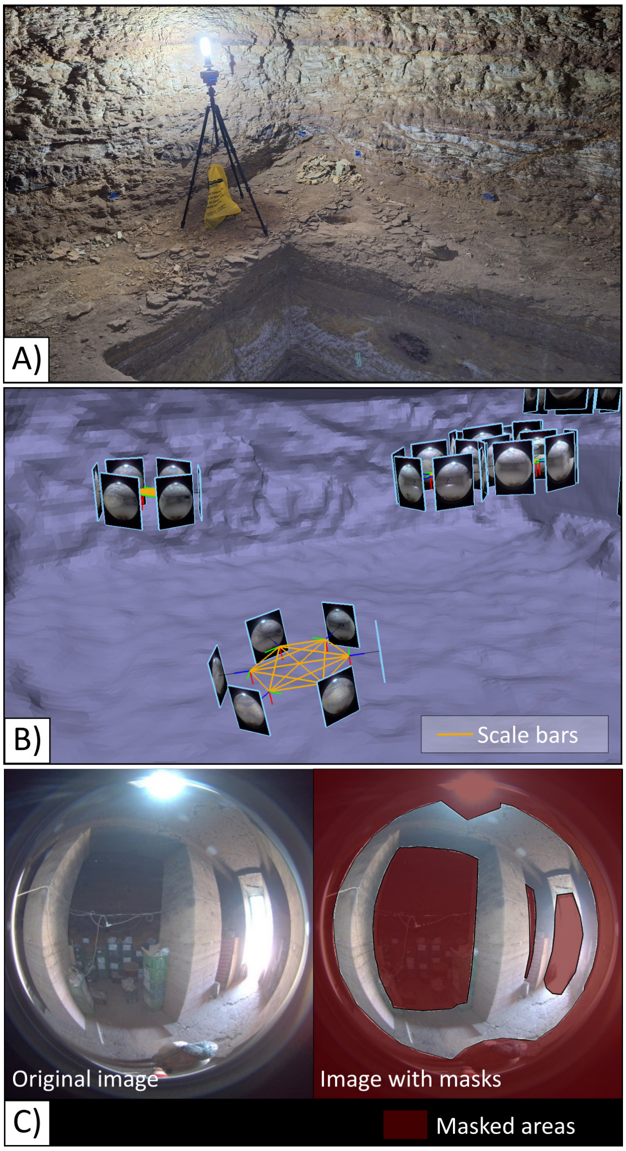

Figure 3. SP data acquisition and processing: a) Kandao Obsidian Go with integrated LED system in QH36; b) Photogrammetric orientation of fisheye images constrained by pre-calibrated inter-sensor distances (scale bars); c) Example of digital masking applied to exclude non-interest objects.

Following the proposed workflow, a Faro Focus X130 laser scanner was deployed (Figure 2a). It was configured for high-density acquisition (approximately 7 mm at 10 m) without color registration to prioritize geometric capture speed, averaging 5 minutes per scan. The QH36 tomb required 60 scans, while the cave was fully surveyed with 11 scans. Registration was facilitated by maintaining large overlaps between adjacent stations. The final registered point clouds (Figure 2b and Figure 2c) were georeferenced using targets (GCPs) surveyed via total station at the site entrances. This approach substantially reduced traditional surveying time. Additionally, the high-density TLS data provided a high-definition reference for the targets used to georeference secondary products (Figure 2c). Finally, the TLS data underwent a filtering process to remove non-architectural elements; Figure 2d illustrates the point cloud before and after removing archaeological equipment.

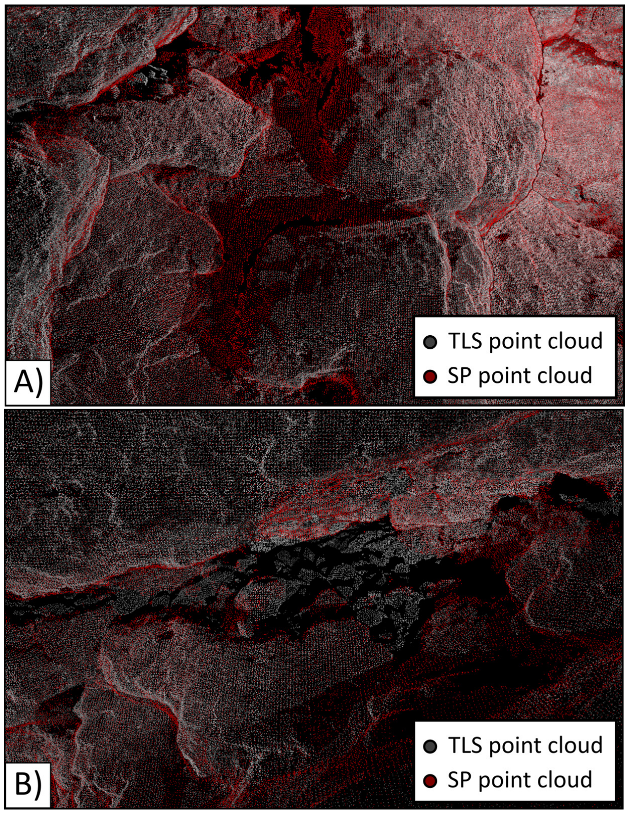

Figure 4. Integration of TLS and SP point clouds: a) detailed view of SP point cloud filling TLS occlusions; b) detailed view of a rock fissure where only TLS points were acquired due to lighting constraints for SP.

Spherical Photogrammetry (SP) was implemented using a Kandao Obsidian Go 360-degree multi-camera equipped with an integrated 360-degree LED lighting system to ensure homogeneous illumination (Figure 3a). This device features six fisheye sensors with a 220-degree field of view, providing extensive overlap. Given that SP acquisition is significantly faster than TLS, a higher density of stations was utilized to guarantee full coverage, balancing the number of images against processing time. Photogrammetric orientation was performed on the raw fisheye images, adhering to the constraints (scale bars, Figure 3b) derived from pre-calibrated inter-sensor distances (extrinsic parameters), as recommended by Pérez-García et al. (2024). To refine the model, 3D meshes derived from the TLS data were used to generate masks for SP images, excluding non-interest objects (e.g., crates). Figure 3c demonstrates how these masks allow the photogrammetric process to focus solely on the relevant geometry and texture. The resulting SP point cloud serves to supplement TLS gaps (Figure 4a). However, in the case of the cave, some dark areas—such as deep fissures—included only points from TLS, despite the higher number of SP stations compared to TLS positions (Figure 4b). Finally, the enhanced images provide a comprehensive texture map for the final 3D fused model (Figure 5).

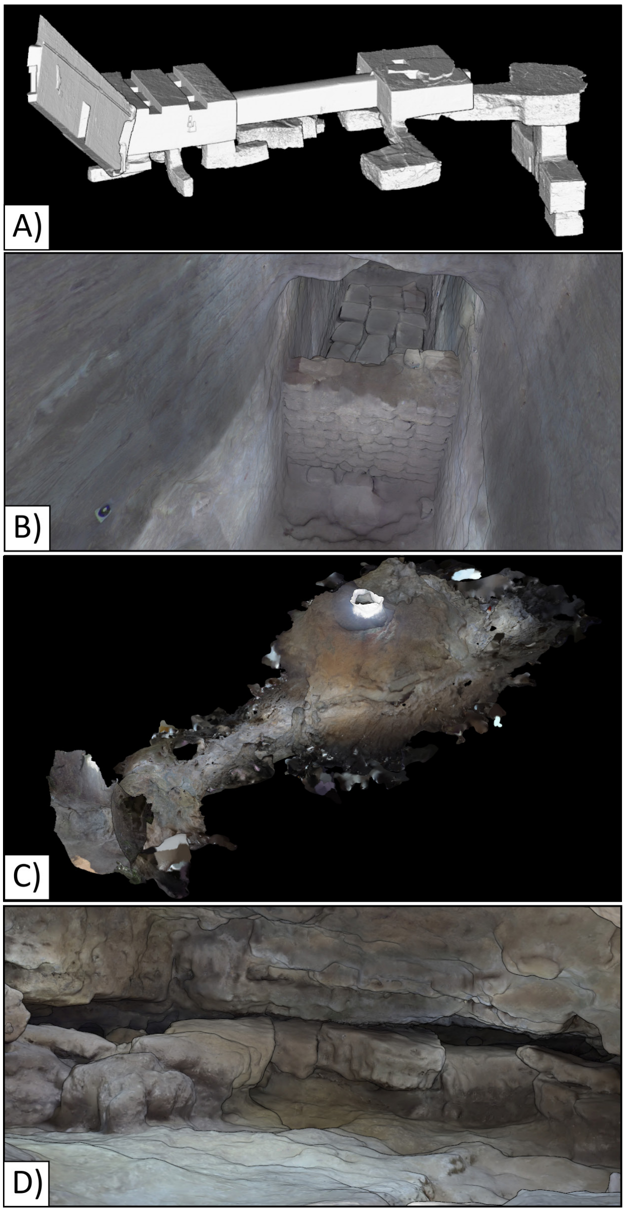

Figure 5. Examples of the results obtained in this study: a) 3D mesh of QH36; b) 3D model of the main burial chamber of QH36; c) 3D model of the cave; d) detailed view of the 3D model of the cave.

In addition, to evaluate the capture efficiency of SP versus conventional photogrammetry, both techniques were implemented in the Hall of Pillars of QH36, an area containing various decorated walls. This scene is particularly challenging due to its narrow layout and the presence of several pillars that cause frequent occlusions and restrict the sensor-to-object distance. For this comparison, each lateral nave was surveyed using 18 stations of the 360-degree camera, resulting in 108 fisheye images to cover the area. In contrast, the survey using conventional photogrammetry was conducted with a Sony Alpha 6000 equipped with a wide-angle lens (16 mm focal length), requiring 238 photographs. Under these conditions, the SP survey was at least six times faster than the conventional approach. Figure 6 presents a comparison of two orthoimages (at 1 mm resolution) of a decorated wall within this hall. The comparison highlights that while the conventional camera offers superior radiometric response and fine detail, the 360-degree camera provides lower definition of the decorations (Figure 6).

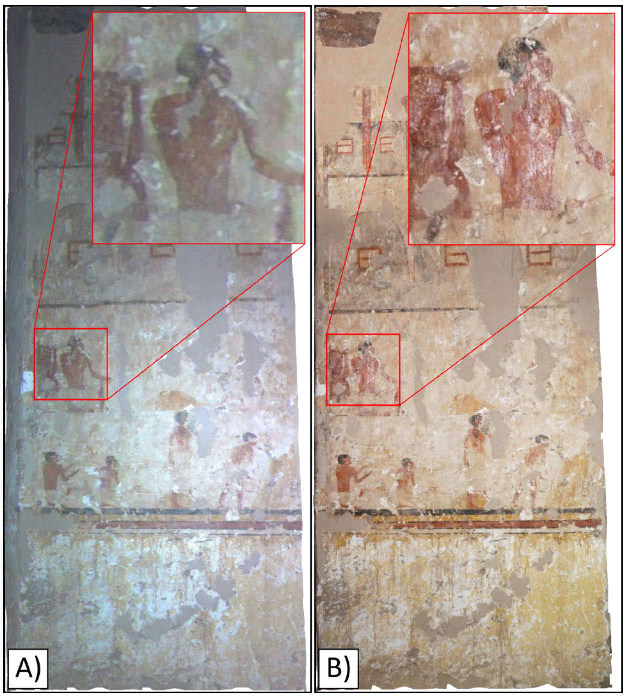

Figure 6. Comparison of orthoimages obtained with 360-degree and pinhole cameras in QH36: a) 360-degree camera; b) pinhole camera.

4. Discussion

The results demonstrate the viability of this integrated approach for rapid data acquisition without compromising product quality. Geometrically, the TLS-based framework achieved high precision, with registration errors consistently below 0.5 cm. By extracting GCPs and CPs directly from the TLS point cloud, we significantly reduced the reliance on total station surveying, thereby increasing field efficiency. Regarding texture, SP proved to be at least six times faster than conventional photogrammetry when considering a comparable number of images; however, this efficiency gain is even more pronounced when accounting for the superior field of view provided by fisheye lenses, which significantly reduces the total number of stations required for full coverage. In fact, in extremely constrained environments, the use of conventional photogrammetry can be inviable due to the impossibility of maintaining adequate standoff distances and overlaps. The ability to deploy more SP stations compared to TLS positions reduced the camera-to-object distance, minimizing occlusions and providing superior radiometric consistency.

However, in environments like the natural cave, the geometry of narrow and unilluminated spaces is more effectively captured using TLS. Laser-based techniques can access deep fissures, acquiring points within them, whereas image-based techniques struggle in such scenes due to poor lighting conditions that generate deep shadows or "black holes" in the data. This necessitates an increase in the number of TLS stations for irregular surface geometries compared to less complex environments, such as polished walls. Furthermore, while the SP sensors achieved a positional accuracy of approximately 3 cm, it is important to note their limitations; compared to conventional sensors, 360-degree cameras exhibit lower resolution and higher distortion.

The comparison between the use of a conventional pinhole camera and the 360-degree camera has yielded significant insights. The conventional camera offers superior radiometric response and detail, aided by controlled flash lighting and optimized exposure parameters per frame. In contrast, the SP system utilizes a fixed lighting source that varies in intensity depending on the distance to the object; furthermore, exposure levels often differ across individual sensors, complicating the radiometric consistency of the stitched output. Therefore, the choice of SP should be driven by the documentation objective. For "raw" or complex areas with numerous occlusions—such as undecorated burial chambers or natural caves—SP is highly recommended for its speed and coverage. However, for high-precision documentation of delicate decorations or inscriptions, conventional photogrammetry remains the benchmark. This inherent limitation of current SP technology must be considered when planning documentation projects. Nevertheless, the rapid evolution of 360-degree sensors suggests that future models with enhanced resolution and improved radiometric image quality will progressively mitigate these issues. Finally, the mode of capture (static vs. video) remains a key consideration. While 360-degree videogrammetry further accelerates acquisition by removing the need for tripod setups, it introduces challenges such as operator visibility, lower per-frame resolution, and motion blur. In low-light interiors, these factors can exacerbate drift issues, compromising both geometric and radiometric integrity (Gómez-López et al., 2025).

5. Conclusions

The 3D documentation of "narrow scenes" in heritage sites—exemplified by the Egyptian tomb of QH36 and the Cueva de la Lobera—demands a delicate balance between high geometric precision and extreme fieldwork efficiency. This research has successfully validated an integrated methodology that leverages the strengths of Terrestrial Laser Scanning (TLS) and Spherical Photogrammetry (SP) to overcome the physical and logistical constraints of confined spaces. The use of TLS as a primary geometric backbone ensured high precision, with registration errors consistently below 0.5 cm. Furthermore, extracting Ground Control Points (GCPs) directly from the TLS point cloud proved to be a highly effective strategy, minimizing the reliance on traditional surveying (e.g., total stations) and significantly reducing time in the field.

Spherical Photogrammetry demonstrated a definitive advantage in environments where conventional photogrammetry is often inviable. Due to the ultra-wide Field of View (FoV) of fisheye lenses, SP achieved full coverage with significantly fewer stations, proving to be at least six times faster than pinhole-camera workflows. This efficiency is critical in active archaeological sites or locations with restricted access permits. The integration of both techniques allowed for a "best-of-both-worlds" result: while TLS effectively captured complex geometries in deep fissures and unilluminated cracks—where image-based techniques often fail—SP provided realistic radiometric textures and successfully filled gaps caused by TLS occlusions, thanks to the higher density of stations enabled by the speed of this technique.

Furthermore, the methodology proved robust in handling "living" archaeological scenes. The use of adaptive capture strategies and digital masking (based on preliminary TLS meshes) allowed for the effective removal of non-interest objects, such as equipment and crates, that could not be physically removed from the site. This ensured a clean and professional final 3D model without disrupting site logistics.

This study concludes that while SP is the optimal choice for the rapid documentation of structural areas and complex occlusions, conventional photogrammetry remains the benchmark for high-resolution documentation of delicate inscriptions or decorations. Therefore, a hybrid approach—tailoring the sensor choice to the specific documentation goal—is recommended for complex heritage sites. Ultimately, the evolution of 360-degree sensors and multi-sensor fusion algorithms provides a promising path for heritage documentation. Future research should focus on the ongoing improvement of the radiometric quality of SP sensors and the potential of 360-degree videogrammetry to further accelerate these workflows without compromising geometric integrity.

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