ISPRS Annals of the Photogrammetry, Remote Sensing and Spatial Information Sciences, Volume X-M-2-2025
30th CIPA Symposium “Heritage Conservation from Bits:
From Digital Documentation to Data-driven Heritage Conservation”, 25–29 August 2025, Seoul, Republic of Korea

Investigating the Accuracy of a 360° Camera for 3D Modeling in Confined Spaces: 360° Panorama vs 25-Rig Compared to TLS

Georgios Kafataris, Dimitrios Skarlatos, Marinos Vlachos, Athos Agapiou.

C.U.T, Cyprus University of Technology, Cyprus – (gil.kafataris, dimitrios.skarlatos, marinos.vlachos, athos.agapiou)@cut.ac.cy

Keywords: Low-cost Photogrammetry, 3D Reconstruction, Underground Confined Tombs, 360° Camera, 25-rig Cameras, TLS.

Abstract

This study investigates photogrammetric solutions for surveying confined underground environments using a small and affordable 360° camera, applied in Tomb 4 at the UNESCO World Heritage Site, Tombs of the Kings in Paphos, Cyprus. Conducted within the framework of the ENGINEER project, this study evaluates the performance of a low-cost 360° 25-lens camera by comparing it to a terrestrial laser scanner (TLS) system used as a reference. The primary objective is to assess the suitability of the 360° camera for 3D documentation in restricted spaces, and to explore its potential application in conservation and restoration efforts at archaeological sites. Two different approaches were tested: using the camera images as 360° panoramic photos or as 25-photos rigid rig setup. The study analyses the accuracy of these methods by generating Point Clouds (PCs) and comparing them to the TLS reference dataset using metrics such as cloud-to-cloud distance, surface roughness, and PC density. In addition, a visual assessment was conducted.

1. Introduction

Recent years have seen a growing interest in the use of 360° cameras for 3D reconstruction, particularly in scenarios where traditional methods where use of static TLS may be restricted by physical dimensions, acquisition time, or budget. While static TLS remains a standard for high-precision PC datasets, it often requires multiple scan positions increasing acquisition time, and experienced personnel in terms of handling and position selection factors that can be challenging in confined or complex environments such as caves, tombs, or narrow corridors. At the same time, the quality of images captured is good only for assigned color to the PC rather than to used for texture, which in some applications, such as Virtual Reality visits or identifying and locating cracks, is crucial.

In contrast, 360° panoramic cameras, like the XPhase Pro X2, offer a lightweight, low-cost, and easy to deploy alternative. These devices capture full spherical imagery in a single acquisition, providing two primary approaches for 3D modeling: (1) the stitched panorama, which can be used for visualization or photogrammetric reconstruction using spherical projections, and (2) the multi-view photogrammetry approach, where the raw images from each lens (25 in the case of XPhase Pro X2) are processed as individually poses in a rigid rig, using Structure-from-Motion (SfM) pipeline to perform self-calibration and estimate the parameters of the rig.

For this paper, the challenge is to examine if these cameras can be considered reliable and user-friendly in difficult environments, such as narrow tombs with limited lighting. The use of TLS in such environments is usually not the most preferable since they cannot be positioned for measurements, for example in narrow tomb niches.

This paper carried out as part of a broader initiative within the ENGINEER project. The project aims to foster collaboration between experts in geomatics and civil engineering, promoting best practices for the documentation and structural analysis of archaeological and cultural heritage sites in Cyprus through 3D modeling. In that sense, identifying, locating, classifying and marking cracks in the monument is important.

From both geometric and geotechnical standpoint, the goal is to establish practical, reproducible workflows that facilitate long-term monitoring of monuments and heritage sites. The findings presented here also provide a valuable resource for structural analysts, who can reuse detailed 3D models with texture data to detect and track structural changes, such as material degradation, evolving crack patterns, or other signs of deterioration over time.

1.1 Case study: Tomb 4 – Tombs of the Kings, Paphos, Cyprus

This paper addresses key challenges associated with surveying objects that are difficult to reconstruct, such as cylindrical columns, uneven and rough surfaces such as walls, confined underground areas, narrow spaces including tombs, chambers, and corridors. These challenges include poor lighting conditions, limited space for instrument placement as well as limited time for data acquisition. The study was conducted in Paphos, Cyprus, within the UNESCO World Heritage Site of Kato Paphos, specifically at the Tombs of the Kings necropolis. This paper focuses on Tomb 4 (Figure 1, 2), which is the second case study within the broader context of the ENGINEER project, coordinated by the Cyprus University of Technology (Agapiou et al., 2023), which aims to support the recording, documentation, and monitoring of cultural heritage.

More specifically, the basic comparisons for this paper were made at the entrance to the small chamber of the tomb, a ~3*3m space, while more general comparisons were made for the entire tomb, which has dimensions of ~10*10m.

Figure 1. Tomb 4 -Atrium.

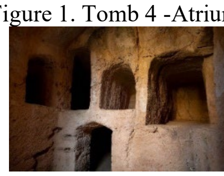

Figure 2. Tomb 4 - Chamber.

1.2 Motivation

The use of 360° cameras in cultural heritage is emerging as a practical method for generating 360° panorama, 3D PCs and models, especially in environments where traditional techniques such as TLS face limitations, or the cost of a TLS is out of budget. These compact, lightweight devices are well-suited for documenting complex or confined heritage sites such as tombs, chambers, and underground structures, where space constraints in conjunction with minimum TLS distance and restricted access hinder conventional survey setups. In such cases, the use of 360° cameras for 3D reconstruction and generation of a dense PC, seems a valid alternative. Within this methodology, two distinct approaches have been tested: the use of stitched panorama images as produced by the camera, and the processing of the 25 photos as an individual rigid frame of photos. The 360° camera used for this testing was the XPhase Pro X2 camera with 25 eight Mpixel sensors, each one using a normal lens. This approach is rather unique among the variety of consumer 360° cameras, which normally use rigs of 2-6 sensors with fisheye lenses. Such implementation although capable of producing 360° stitched panoramas, is not favorable for 3D reconstruction because of high distortions on the edges of the photos, which regardless the in-camera undistorting effect, are challenging for image matching during SfM processing. Normal lens images, without the extreme fisheye effect are much favorable in SfM processing. Panoramic images provide rapid, immersive documentation that can also be used for 3D reconstructions using spherical projections. In contrast, the 25-rig image approach captures simultaneous views from multiple angles, offering high overlap and multi-baseline geometry. The use of panoramic images straight out of the camera allows for a quick processing pipeline, but the stitching effect and the unpredictable stich lines do not allow for proper spherical camera calibration, hence large image coordinate residuals in the final Bundle Adjustment (BA). On the other hand, the use of the 25 photos as a rigid rig, allows for individual camera calibration, potentially lower image coordinate residuals, better 3D reconstruction, and the ability for direct scale extraction if the rig is with pre-calibration.

As image-based reconstruction technologies continue to advance, 360° cameras are poised to play an increasingly significant role in cultural heritage documentation that offering a flexible, scalable, and cost-effective alternative or complement to traditional 3D acquisition tools.

2. Related work

Today, there are still challenges in achieving the same level of geometric accuracy, density, and surface detail as TLS, especially when relying on consumer-grade cameras. The comparison between TLS and image-based 360° methods is an active area of research, with recent efforts focusing on evaluating their respective strengths and weaknesses in terms of accuracy, completeness, portability, and adaptability to constrained environments. Several studies have explored the use of 360° cameras to create 3D PCs and models, demonstrating promising results, particularly in cultural heritage documentation and indoor mapping. In this chapter, some past cases that have been implemented will be briefly described.

Skarlatos, D., et al. (2024) attempted to compare frame cameras with traditional methods against 360° stitched panorama images captured using a commercial low-cost camera. The study found that while the 360° camera provides user-friendly operation and high data density, it also introduces increased noise and variability. In contrast, traditional methods, though more time-intensive, deliver more consistent and accurate results. The findings indicate that a hybrid approach could enhance both data quality and acquisition efficiency, positioning the 360° multi-lens camera as a viable, budget-friendly photogrammetry solution for cultural heritage documentation.

Perez-García, J., L., et al. (2024) explored the photogrammetric potential of 360° cameras for documenting complex heritage environments in the Aswan Necropolis, Egypt. Their aim was to leverage the wide field of view offered by these cameras to reduce the number of images needed compared to conventional methods, while also addressing challenges related to lens geometry. Using a multi-sensor camera with six fisheye lenses, they applied photogrammetric workflows to various funerary structures. The study involved analyzing different types of spherical images produced through various stitching methods and comparing the outcomes of image orientation using both stitched and original fisheye images. They also investigated the use of fisheye imagery to model complex scenes with minimal reliance on Ground Control Points (GCPs), instead applying distance constraints derived from a prior extrinsic calibration. The results showed comparable accuracy to traditional point-based methods and highlighted the strengths and limitations of each imaging approach, offering practical guidance for heritage documentation.

Janiszewski, M., et al. (2022) presented a method for rapid photogrammetric reconstruction of tunnels using a 360° camera. The study was conducted in a 10-meter section of an exposed rock tunnel in Espoo, Finland. Images were captured from 27 positions using the 360° camera, and a 3D model was generated using SfM photogrammetry. The model was compared to both a reference laser scan and a model created with a traditional DSLR camera. Results showed that image acquisition with the 360° camera was three times faster and the process was simpler and less error prone. The model achieved a distance accuracy error of just 0.0046 meters relative to the laser scan. Additionally, discontinuity orientations were extracted remotely from the model, showing close alignment, within 2 to 5° with manual compass measurements, demonstrating the method's effectiveness for tunnel documentation.

Barazetti, L., et al. (2018) investigated the potential of achieving accurate metric reconstructions using a low-cost 360° camera which costs under €300. Their experiments showed that millimeter-level accuracy is possible during image orientation and surface reconstruction, as verified against check points measured with a Total Station (TS) and laser scanning PCs. The study highlights key practical guidelines for image acquisition and emphasizes the role of GCPs in correcting network deformations during BA, particularly in long image sequences with challenging geometries. Also, they explored the creation of orthophotos from 360° images, which capture the entire surrounding scene. Several case studies were presented, where 360° cameras proved more effective than traditional central perspective cameras. The authors conclude that 360° cameras are especially advantageous for surveying long, narrow spaces and confined interiors such as small rooms, making them a valuable tool for specific photogrammetric applications.

Jiang, San., et al. (2024) presented a thorough review of the current advancements in 3D reconstruction using spherical images, covering key aspects such as data acquisition, feature detection and matching, image orientation, and dense matching. They also explored emerging applications and discussed potential future directions in the field. Their study provided valuable insights and serves as a foundation for guiding upcoming research efforts.

3. Equipment and methodology

As mentioned previously, the goal was to compare two separate approaches based on a 360° camera (Xphase) versus TLS data as a reference. TLS is considered as reference in terms of data acquisition methodology, because it is well adopted in CH applications, and offers millimeter-level accuracy, making it perfect for documenting complex architectural features, sculptures, inscriptions and textures. Therefore, the 360° camera will be described below, although at a fraction of its cost (25-30 times less expensive), still needs to be compared with the existing established technology.

3.1 360° camera: Xphase Pro X2

The XPhase is a lightweight 360° camera, weighing just 250 grams and costs ~1000 euros. By default, the camera operates in HDR mode, capturing six bracketed photos to produce, ensuring the best possible final image.

The XPhase offers two post-processing modes for exporting recorded photos: stitched panoramas and 25-camera rig RAW output. For the latter mode, each lens-sensor exports all record bracketed RAW images, in DNG format. Given that by default captures three bracketed photos for HDR processing, at each position (3 photos x 25 lenses x 8 Mpixels) 600 Mpixels are recorded in RAW format. This requires a lot of storage space, but most importantly a substantial recording time to the internal USB storage, which increases if a 5 or 6 bracketing mode is selected.

In panorama mode, a high-resolution panorama image with a resolution of 16,384 × 8,192 pixels (134 MPixels), is generated by combining all raw data frames. These JPEG-compressed panoramas are useful for quick visualization but may contain stitching artifacts.

In contrast, the 25-camera rig mode captures simultaneous RAW images from each 1/3.2" BSI CMOS sensor (8 MPixels each, 3.85 mm focal length). This uncompressed, unstitched format is more appropriate for photogrammetric processing, allowing better camera distortion modeling, and overall better BA.

In both modes, the entire environment is offered in a single shot, covering 360° horizontally and 180° vertically, effectively eliminating blind spots and ensuring complete spatial coverage from a single location, something that improves alignment between images in photogrammetry applications. This overlay is convenient for applications in interior heritage structures and narrow or confined spaces (e.g. tombs, caves, small rooms). The synchronous capture ensures consistency under changing lighting or with moving subjects, making it especially useful for complex or fragile indoor environments where accuracy and temporal consistency are critical. The camera should be securely mounted on a tripod to provide stability during capture, especially for long captures in low lighting conditions and HDR processing of the multi-bracketed exposures. Since all 25 cameras obtaining simultaneously, using a fixed tripod effectively eliminates the risk of scene movement between shots, a common problem in traditional photogrammetry workflows that rely on sequential image acquisition. In addition, tripod allows the operator to remotely trigger the camera without being within each image, effectively reducing the recorded area and challenging the SfM process.

Figure 3. The 360° camera - Xphase Pro X2.

3.2 The basic workflow

A workflow began with data acquisition using TLS and then 360° imagery data. TLS data were processed using the Faro Scene softwere for co-registration and georeferencing with control points in the UTM36N coordinate system, resulting in the creation of a reference PC. The 360° panoramic images captured were post processed to generate 360° panoramas (134 Mpixels). The data captured were HDR processed so that in each position 25 LDL JPG were created. Each dataset was processed in Agisoft Metashape using coded GCPs and a PC of each dataset was generated. Both PCs were compared against a reduced TLS PC in CloudCompare software. For benchmarking purposes, the datasets were cropped into the same area and aligned using the Iterative Closest Point (ICP) algorithm, to avoid systematic errors. Particular attention was given to the inner chamber, where all three datasets were re-aligned with ICP for more detailed accuracy comparison. The evaluation relied on several key metrics: cloud-to-cloud distances to quantify geometric deviations, roughness to assess local surface irregularities, surface density to evaluate the detail captured by each dataset, and visual completeness to examine how thoroughly each dataset covers the reference PC. This approach ensured a rigorous, consistent, and quantifiable comparison of the datasets in terms of accuracy, resolution, and spatial coverage.

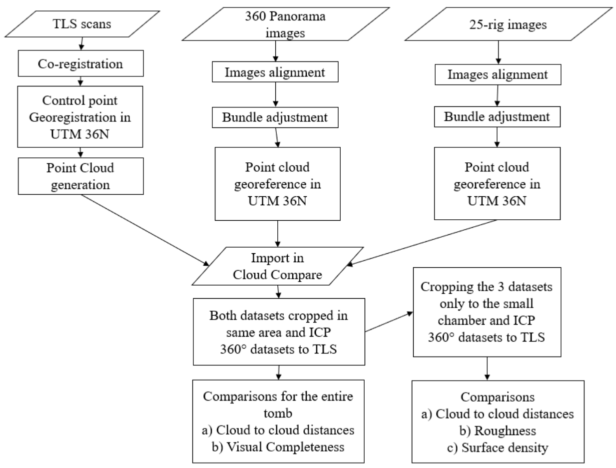

Figure 4. The basic workflow

3.2.1 Faro M70 acquisition and processing

TLS scans were carried out at short distances between stations (~3–7 meters) to guarantee sufficient overlap and clear visibility to the checkerboard targets. The scanner was also placed in more challenging spaces, such as narrow corridors behind columns, holes and chamber recesses, ensuring tomb completeness as possible. The scanner was mounted on a special tripod and its height was adjusted based on the spatial characteristics of each space. Additionally, RGB images were acquired to colorize the PC data. To fully document the entire Tomb, 41 double-pass scans were conducted, each lasting ~2 minutes (total ~5 minutes including tripod adjustment), with a resolution of 7.7mm/10m and consisted of 28M points.

To georeference the laser data, 11 checkerboard targets were surveyed using a TS, with reference to three control points established via RTK GNSS. The checkerboard targets were strategically placed with optimal geometry at both high and low spots, around the perimeter walls of the tomb, as well as within the inner chamber. Placing targets inside the chamber was especially crucial to ensure accurate alignment between the PCs captured in the atrium and those within the small chamber (the same applies for the 360° datasets).

The TS observations were integrated with the RTK positions, allowing the checkerboard targets to be accurately transformed into the UTM36N coordinate system. The residual mean georeferencing errors (distance, horizontal, and vertical) were below 0.005m, reflecting a high-quality alignment, which highlights the high internal accuracy between scans.

It is noted that the same 11 targets were used for the BA and georeferencing of the two 360° camera datasets.

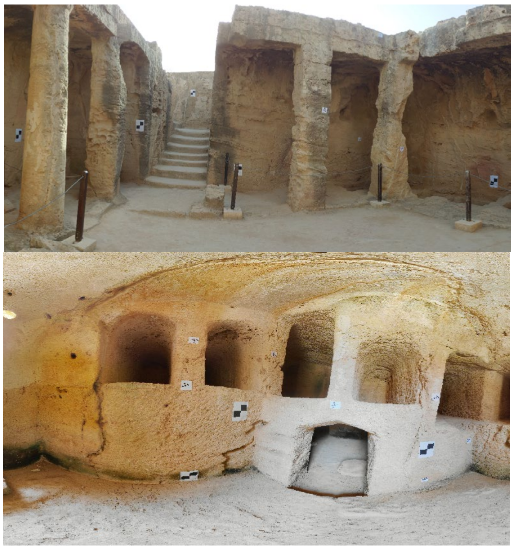

Figure 5. The geometry of the checkerboard targets. The atrium (above) and the chamber (below).

3.2.2 The camera 360° acquisition and processing

As 360° technology has been integrated into photogrammetric workflows and software recently, without many applications on the field so far, there is currently a lack of established literature or standardized acquisition protocols. As a result, image capture positions were selected in relaxed positions. However, due to the nature of 360° imagery, each capture inherently provides high coverage with neighboring images, eliminating the need for carefully pre-planned acquisition path to ensure enough coverage for orientation and adjustment. The operator's primary responsibility is simply to select positions following object's geometry. This significantly reduces the complexity of the task and minimizes the operator's workload. Consequently, photogrammetric data acquisition using 360° cameras becomes an effortless process even for beginners who may have little or no experience with traditional photogrammetric protocols.

Although image capture with a 360° camera is inherently faster than with TLS (~1 minute per shot), the overall acquisition time is often longer in practice due to the large volume of raw data generated and the relatively slow data storage speed. Like TLS, the operator must move out of the camera's field of view before each capture, which adds further delay, bringing the effective capture time to around ~1.5 minutes per position.

To ensure complete coverage of the tomb, 117 images were acquired including the tombs upper base, the atrium, and the interior spaces of the chamber.

The two Xphase camera setups for one random shot are presented at Figure 6.

Figure 6. The 25-rig cameras (left) and the 360° Panorama (right).

The basic parameters of the acquisition are presented in Table 1.

Dataset	TLS	360° camera
Instrument	Faro Focus M70	XPhase Pro X2
Sensor resolution	7.7mm/10m	25 x 8 MP, 1.4μm pixel
Real focal length [mm]	-	3.85
Number of scans/images for entire Tomb	41 scans	117 panoramas (2925 photos in total)
Survey period	June 2024	June 2024
Acquisition time for entire Tomb [mins]	205	175
Average time per scan/photo [mins]	5	1.5

Table 1. The acquisition parameters

The two photogrammetric datasets were processed in Agisoft Metashape with similar parameters. For images alignment, guided matching was selected, with key point/MPixel and tie points set at 1,000 and 4,000 points, respectively. Prior to the BA optimization, the sparse cloud was cleaned from outliers. It should be noted that in both approaches ~70% of initial tie points were considered as outliers and were deleted. An issue with duplicate surfaces arose, which was resolved by filtering out points that appeared in only 2 images.

Figure 7. The 360° images block geometry. The entire tomb (above) and the chamber (below).

For the 360° panoramas BA optimization, a total of 117 images were processed using automatic camera calibration, supported by the 11 well-distributed TLS-derived GCPs, each marked in 5 images to enhance the accuracy of the adjustment. This approach resulted in a dense PC with a GCPs reprojection error of 2 pixels and a total RMS error of 0.015m. The 2-pixel GCPs reprojection error is within acceptable limits for equirectangular panoramas, which are more prone to distortion than conventional perspective images. The low RMS error demonstrates strong spatial accuracy and effective alignment with the UTM36N based reference coordinates. These results highlight that, despite the inherent challenges of working with stitched panoramic imagery and autocalibration, the workflow produced a geometrically consistent PC suitable for applications in cultural heritage documentation and spatial analysis.

Using 117 image sets from the 25-rig configuration of the XPhase - amounting to 2925 individual images - combined with camera autocalibration and the 11 GCPs, the resulting 3D PC achieved a GCPs reprojection error of 0.7 pixels and RMS error of 0.005m (each GCP marked on 5 images). This represents a significant improvement in both image-space and real-world accuracy compared to panorama scenario with 117 stitched 360° panoramas, which produced a reprojection error of 2 pixels and total RMS error of 0.015m. The lower reprojection error in the 25-rig setup demonstrates the geometric advantage of using individual perspective images, which are more accurate for SfM algorithms than panoramas which suffer from edge stretching and spherical distortion. Additionally, the 25-rig images offer multi-angle redundancy, and improved depth perception, all of which contribute to a more robust and accurate BA. The significantly lower RMS error confirms that the 25-rig approach provides better georeferencing fidelity, especially when supported by GCPs. In summary, while 360° panoramas offer speed and simplicity in process, the 25-rig method offers superior geometric precision and PC accuracy, making it more suitable for high-resolution cultural heritage documentation and detailed spatial analysis. The superiority of 25-rig over 360° panoramas is also reflected in the tie points RMS reprojection error, with panoramas yielding a higher error of 2.5 pixels, compared to 1 pixel for the 25-rig configuration, confirming the enhanced geometric accuracy and stability provided by the multi-view perspective approach.

After the BA optimization, the PCs were reconstructed. A point confidence filter was applied, and the worst points (values 0-1 out of 0-255 confidence range provided by Agisoft) were deleted from both datasets. Based on the results, 55% and 40% points of the initial PCs were deleted as "bad", for 360° panoramas and 25-rig, respectively. This filtering result confirms that, while both methods are usable, the 25-rig configuration delivers a more reliable and structurally sound PC, especially in complex scenes. The panorama-based approach, while efficient for capturing full surroundings quickly, comes with higher noise and uncertainty, which needs heavier post-processing to isolate high-quality data. In cultural heritage or high-accuracy workflows, this suggests the 25-rig method is more suitable when precision and completeness are priorities.

It is important to note that, due to the high point density, the TLS PC was subsampled to a resolution of 0.001m for comparison purposes. Additionally, all three datasets were cropped to the same area, both for the entire tomb and specifically for the chamber, ensuring consistency in the evaluation. For a more objective and accurate comparison, the photogrammetric PCs were aligned to the TLS reference using the ICP algorithm in both cases, effectively minimizing residual alignment errors and ensuring a consistent geometric reference across the three datasets.

The following table shows the basic processing parameters for the 3 datasets.

Dataset	TLS (Ref)	360° Panorama scenario	25-rig scenario
Number of scans/photos	41	117	2925
Total Mpixels	-	15678	23400
Average GSD [mm]	-	0.8	0.8
Average distance to object [m]	2	1.7	1.4
Average tie point multiplicity	-	4	2.5
Reprojection error [pixels]	-	2.5	1
Control point RMS (Total 3D) [m]	0.005	0.015	0.005
Initial tie points [K]	-	156	800
Tie points after cleaning [K]	-	126	600
Keeping only 3-ply tie points [K]	-	56	200
Control points reprojection error [pixels]	-	2	0.7
Final clipped [Mpoints-Entire tomb]	550 (1mm subsampled)	133	165
Final clipped PC [Mpoints-Chamber]	60 (1mm subsampled)	25	17

Table 2. Post-processing parameters and results.

4. Comparisons

Comparing cloud-to-cloud (C2C) distances, roughness, and point density between TLS and photogrammetric reconstructions from 360° panoramas and 25-rig images is essential for evaluating the geometric accuracy and detail preservation of alternative acquisition methods in cultural heritage documentation. **C2C distances** analysis provides a direct quantitative assessment of how closely the photogrammetric PCs replicate the high-accuracy TLS reference, highlighting deviations and potential systematic errors. **Roughness** analysis further reveals the level of surface detail and potential noise in the reconstructions, which is particularly important for capturing fine architectural or sculptural features. **Point density** comparisons help to assess the spatial resolution and completeness of coverage, identifying areas where detail may be lacking or oversampled.

For the computation of roughness and surface density, a local neighborhood radius of 0.025m was applied in this study. The results of the comparison are illustrated graphically in the corresponding figures.

4.1 Chamber comparisons

- C2C distances

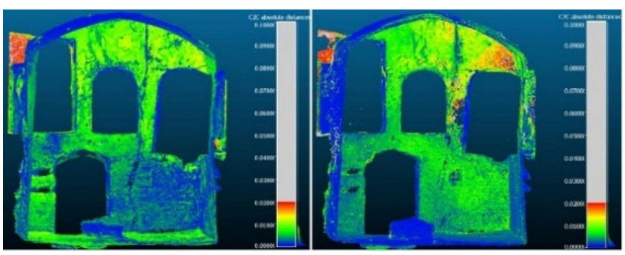

Figure 8. C2C distances against TLS. 360° panorama (left) and 25-rig (right).

Both results display positive differences ranging from 0 (blue) to 0.02m (red), indicating that the photogrammetric clouds consistently lie slightly outside the TLS surface, suggesting a small-scale difference. This systematic offset may arise from limitations in photogrammetric depth accuracy, especially due to panoramic stitching distortions or imperfect camera calibration. Quantitatively, the 360° panorama PC yielded a mean deviation of 0.0042m, a standard deviation of 0.004m, and an RMS error of 0.0058m. The 25-rig configuration showed slightly improved metrics, with a mean error of 0.0035m, a standard deviation of 0.0045m, and RMS of 0.0057m. Despite the 25-rig having a marginally higher standard deviation, suggesting slightly more local variability, it still achieved a lower mean and RMS error, reflecting better overall alignment and accuracy. This performance difference can be attributed to the multi-view nature of the 25-rig, which offers improved depth reconstruction, fewer occlusions, and more reliable camera geometry compared to panoramic captures.

- **Roughness (r: 0.025m)**

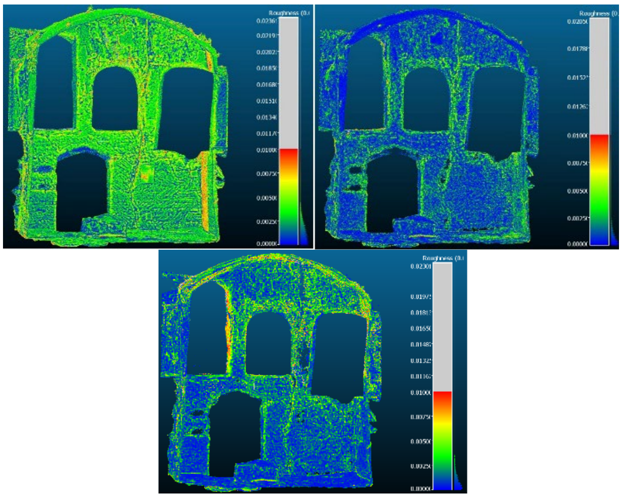

Figure 9. Roughness - TLS (above left), 360° Panorama (above right) and 25-rig (below).

The roughness analysis reveals distinct surface characteristics across the three PCs. Visually, all three datasets display roughness values ranging from 0m (blue) to 0.01m (red). The TLS PC (above left) shows a roughness RMS of 0.0021m, the 360° panoramas (above right) have a lower RMS of 0.0014m, and the 25-rig (below) has a slightly higher RMS of 0.0022m. Interestingly, the 360° panorama dataset exhibits lower overall roughness, which may be misleadingly interpreted as higher surface smoothness. In reality, this likely reflects a loss of fine surface detail and lower point density due to limited parallax and distortion introduced during panorama stitching. The TLS dataset, by contrast, preserves more true surface variations, particularly on textured areas, which is expected from a high-precision scanner. The 25-rig PC, while slightly rougher than TLS in RMS terms, exhibits a more detailed and consistent surface than the panoramas, benefiting from multi-angle photogrammetric depth estimation. The presence of holes, especially in the 360° panorama PC, reflects limitations in reconstruction. The 25-rig performs better with fewer gaps (but notable), while TLS shows the most complete and detailed surface, accurately preserving roughness and minimizing missing data.

- **Surface density (r: 0.025m)**

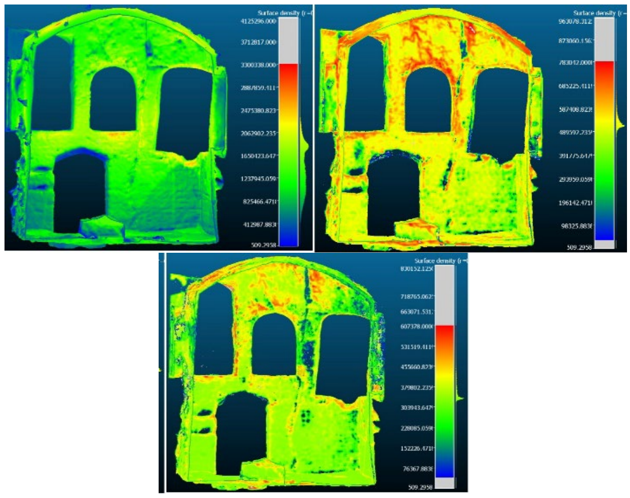

Figure 10. Surface density - TLS (above left), 360° Panorama (above right) and 25-rig (below).

In the surface density analysis, the TLS PC (above left) exhibits the highest density value (1475384 pts/m^2), indicating a very dense PC, but also shows a wider distribution of values compared to the XPhase datasets. This wider spread, as seen in the broad range of the color bar (blue to red), reflects the very high variability in density, which is typical in TLS datasets where some areas, especially those near the scanner, are sampled with extremely high density. The 360° panorama PC (above right), with density value of 542399 pts/m^2, and the 25-rig PC (below) with 372859 pts/m^2, both show narrower distributions, indicating more uniform, but overall lower density. This uniformity, especially in the 25-rig dataset, results from consistent camera spacing and simultaneous capture, but these PCs lack the extremely high sampling peaks found in TLS. The narrower spread is not necessarily better, it simply means the PC lacks the high-frequency density variation present in TLS data. In summary, TLS offers greater overall density and sampling depth, while XPhase-based PCs (especially 360° panoramas) are more uniform but sparse, due to limitations in reconstruction.

4.2 Entire tomb comparisons

In addition to the detailed comparisons performed within the chamber, a C2C distance analysis was also conducted for the entire tomb, allowing for a broader assessment of geometric accuracy. Alongside the quantitative results, **visual completeness** between the clouds was evaluated, highlighting differences in areas where geometry was either missing or poorly reconstructed, often due to limited viewpoints. This visual assessment is essential for identifying gaps, surface discontinuities, and blind spots that directly affect the usability and reliability of 3D models, especially in cultural heritage documentation where detail preservation and spatial continuity are vital.

- **C2C distances**

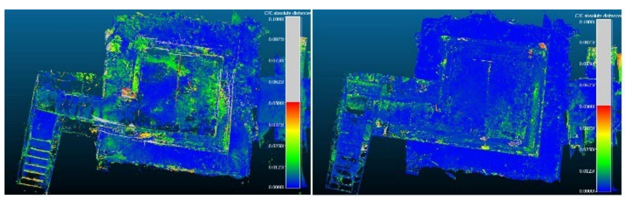

Figure 11. C2C distances against TLS. 360° panorama (left) and 25-rig (right).

https://doi.org/10.5194/isprs-annals-X-M-2-2025-139-2025

The C2C distance comparison of the entire tomb, reveals that both the 360° panorama (left) and the 25-rig (right) maintain generally good geometric consistency, with most deviations falling within the 0 to 0.025m range (blue to green). However, localized discrepancies up to 0.05m (yellow to red areas) are visible, particularly around architectural edges and complex geometries. The 25-rig PC outperforms the panoramas in terms of accuracy, with lower mean (0.0034m), standard deviation (0.0056m), and RMS (0.0066m) values compared to the 360° panorama PC, which recorded mean (0.0059m), standard deviation (0.0072m), and RMS (0.0093m). These results reflect a more precise reconstruction from the 25-rig configuration across the full tomb. When compared to the chamber-only C2C results, where the panorama yielded mean 0.0042m and the 25-rig 0.0035m, we observe a slight increase in errors in the full tomb scenario, likely due to increased scene complexity, larger surface variation, and less optimal coverage across the wider area. Therefore, the 25-rig method shows superior and more stable performance.

- **Visual completeness**

Figure 12. Visual completeness checks in atrium. 360° panorama (left) and 25-rig (right).

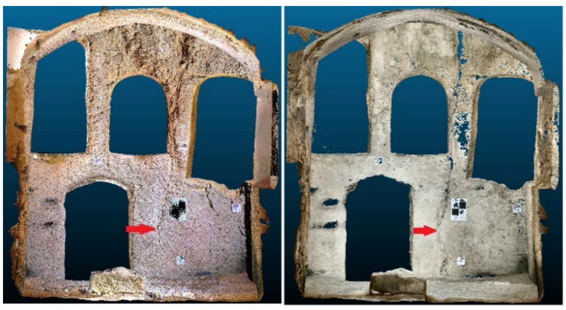

Figure 13. Visual completeness in chamber for crack detection. TLS (left) and 25-rig (right).

The visual completeness comparison between the 360° panorama (left) and the 25-rig PCs (right) in Figure 12, highlights notable gaps in geometry across the ground, wall surfaces, and columns, with the 360° panorama showing more extensive missing areas. These holes are primarily caused by insufficient image coverage, limited viewpoints, and lighting challenges. The lane-like vertical holes along the columns are typical artifacts of photogrammetric reconstructions taken from fixed-height positions, where cylindrical features lack sufficient parallax for proper matching. This issue is visible in both PCs but less severe in the 25-rig due to its multi-angle capture. However, in the narrow corridor behind the columns, which is only 2 meters wide and was captured with fewer images, both PCs suffer from incomplete reconstruction due to constrained geometry and occlusions. In contrast, the atrium area in front of the columns, where more photos were taken, shows much better surface continuity in the 25-rig PC, although even here the strong sunlight on the wall surfaces introduced overexposure, reducing texture detail and impacting the reconstruction quality.

While the TLS PC appears more complete (Figure 13), especially in terms of surface coverage and continuity, it lacks the textural richness and visual clarity needed to confidently identify fine surface features like cracks. In contrast, the 25-rig PC, although less dense and slightly less complete in some areas, offers superior visual detail through its high-resolution texture mapping. This making cracks and surface deformations more visible and distinguishable.

5. Conclusions

The comparison metrics indicate that the 25-rig approach provides a more reliable and complete PC than the 360° panorama method. With an improved acquisition strategy, to accommodate better and more consistent image coverage, full completeness and accuracy like TLS could be achieved.

Although it seems that it is easy to use 360° cameras for acquisition, an acquisition protocol is missing from literature and must be defined the same way that we have established acquisition protocol for standard frame cameras (i.e, 80%-60% forward-lateral overlap rule).

A critical factor that may have influenced the results lies in how Agisoft Metashape processes different input types, particularly stitched 360° panoramas versus multiview images from a 25-camera rig. When using stitched panoramas, Metashape treats each panorama as a single image captured from a single viewpoint, which inherently limits the available parallax information. This lack of parallax reduces the software's ability to generate accurate depth and geometric detail in the resulting point cloud. In contrast, the 25-rig multiview approach provides multiple overlapping images from different angles, allowing Metashape to leverage a higher number of tie points and stronger geometric constraints. Moreover, Metashape is designed to handle multiview stereo reconstruction effectively, especially when cameras are grouped or aligned as a rig, enabling more robust SfM and dense matching. These software-specific behaviors likely contributed to the superior reconstruction accuracy observed in the 25-rig dataset compared to the stitched panoramas and should be taken into account when interpreting the results.

The use of 360° cameras has a functional advantage on closed areas and confined spaces. When the area is so narrow that even a person can hardly fit in the advantage is even bigger.

Undeniably the use of 360° cameras has an advantage in rapid acquisition. This is mainly limited by the fact that the user must hide from the 360° view of the camera, plus the recording rate of the camera especially for the XPhase camera which records at least 3x200 Mpixels per capturing position. The data recording rate is such, that the camera became very hot to touch during our acquisition.

Lighting conditions are critical. The use of tripod and tribal for stability during acquisition, both for lighting as well as for HDR computing is necessary.

Also, illumination had a noticeable impact on the quality of reconstructions for both methods. In the atrium, where lighting was intense, both the 360° stitched panoramas and the 25-rig multiviews produced PCs with more gaps compared to the uniformly lit chamber. However, the 25-rig handled these conditions better, likely due to its multiple viewpoints capturing more redundant information, helping compensate for overexposed or shadowed areas. In contrast, the stitched panoramas, offering a single synthesized view with less parallax, were more sensitive to lighting variations. Capturing in more uniformly lit conditions, such as early morning, late afternoon, or using artificial diffused lighting, can help reduce shadowing and overexposure. This highlights the importance of uniform lighting in photogrammetric capture, especially when using 360° cameras. This outcome is consistent with known photogrammetric principles that strong, directional lighting can create overexposed or underexposed regions, shadows, and reduced detail, all of which hinder feature detection and matching during processing. Uniform lighting, even if lower in intensity, generally improves image quality and feature extraction by minimizing high-contrast edges and shadowed regions. While this observation was not the primary focus of our study, it highlights the importance of controlled lighting conditions in 3D reconstruction workflows, particularly in heritage documentation where environments often vary in illumination. A more systematic analysis of lighting effects could be explored in future work to better understand their influence on different acquisition methods.

Based on our experience with both 360° stitched panoramas and multiple 25-rig multiviews in a confined tomb environment, several practical considerations emerged that can inform preliminary best practices. First, uniform illumination has a significant impact as explained in the previous paragraph. Additionally, cylindrical columns exhibited vertical gaps from base to top, likely due to insufficient vertical coverage and obstructions, a common challenge in confined spaces with limited viewing angles. To improve results, we recommend taking images in multiple vertical planes and ensuring overlap from different angles around this geometry. The camera should be moved around complex features with enough coverage to minimize occlusions, especially in areas with high curvature or detail.

Identifying cracks is better with visual information rather than 3D information from the TLS.

Quality of image is directly related to final (Multi-View Stereo) MVS results. The Xphase implementation is decent for its cost, which is similar to other implementations with two fisheye larger format cameras. The use of narrow lenses with a multiple of cameras allows for high-resolution images, with minimum lens distortion. Still the quality of the lens and the very small pitch of the pixels, pose significant challenge during the MVS process.

Acknowledgements

The authors would like to acknowledge the ENGINEER project. This project has received funding from the European Union’s Horizon Europe Framework Programme (HORIZON-WIDERA2021-ACCESS-03, Twinning Call) under grant agreement No 101079377 and the UKRI under project number 10050486. Disclaimer: Views and opinions expressed are, however, those of the authors only and do not necessarily reflect those of the European Union or the UKRI. Neither the European Union nor the UKRI can be held responsible for them. The authors would also like to thank the Department of Antiquities of Cyprus for providing access to the site and for their support.

References

Agapiou, A., Aktas, Y. D., Barazzetti, L., Costa, A., Cuca, B., D.’ Ayala, D., Kyriakides, N., Kyriakidis, P., Lysandrou, V., Oreni, D., Previtali, M., Skarlatos, D., Tavares, A., Vlachos, M., 2023. Geomatics and civil engineering innovative research on heritage: introducing the “ENGINEER” project. *The International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences*, *48*, 27-32. doi.org/10.5194/isprs-archives-XLVIII-M-2-2023-27-2023

Barazzetti, L., Previtali, M., & Roncoroni, F. (2018). Can we use low-cost 360 degree cameras to create accurate 3D models?.*The International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences*, *42*, 69-75. doi.org/10.5194/isprs-archives-XLII-2-69-2018

Janiszewski, M., Torkan, M., Uotinen, L., & Rinne, M. (2022). Rapid photogrammetry with a 360-degree camera for tunnel mapping. *Remote Sensing*, *14*(21), 5494. doi.org/10.3390/rs14215494

Jiang, S., You, K., Li, Y., Weng, D., & Chen, W. (2024). 3D reconstruction of spherical images: a review of techniques, applications, and prospects. *Geo-spatial Information Science*, *27*(6), 1959-1988. doi.org/10.1080/10095020.2024.2313328

Pérez-García, J. L., Gómez-López, J. M., Mozas-Calvache, A. T., & Delgado-García, J. (2024). Analysis of the photogrammetric use of 360-degree cameras in complex heritage-related scenes: case of the Necropolis of Qubbet el-Hawa (Aswan Egypt). *Sensors*, *24*(7), 2268. doi.org/10.3390/s24072268

Skarlatos, D., Cuca, B., Kafataris, G., Previtali, M., & Agapiou, A. (2024). Low-cost photogrammetry solutions for surveying confined underground spaces: testing the traditional set-up against 360 camera on Tombs of the Kings archaeological site. *International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences*, *48*, 425-430. doi.org/10.5194/isprs-archives-XLVIII-2-W8-2024-425-2024