Low-cost photogrammetry solutions for surveying confined underground spaces: testing the traditional set-up against 360° camera on Tombs of the Kings archaeological site

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Introduction

This study examines the geometric documentation of Tomb 7, which is a UNESCO World Heritage Site and is located in the archaeological site of the Tombs of the Kings in Paphos, Cyprus. This research was conducted under the ENGINEER project and the aim is to compare traditional photogrammetric methods using frame cameras against a 360° multi-lens camera. The purpose of this comparison is to identify reliable, low-cost methods for 3D documentation of archaeological sites, which can be used for structural analysis and systematic monitoring.

Three photogrammetric methodologies were tested: handheld and standard techniques using frame cameras versus a relaxed method employing a 360° multi-lens camera. The accuracy of these approaches was assessed by comparing point clouds generated from each method to a reference dataset created from terrestrial laser scanner (TLS). Key metrics such as cloud-to-cloud distance, roughness, and surface density were analyzed. This work contributes to a broader effort to enhance heritage site documentation and monitoring while exploring efficient, low-cost solutions for challenging survey conditions.

Although the entirety of Tomb 7 was documented, using a combination of aerial and terrestrial photogrammetry, as well as terrestrial laser scanning (TLS), the area of comparison was limited to one wall of the atrium. The comparison was performed on the left wall as entering from the narrow corridor (south-east wall). A large dominant crack was evident on this wall and the geometric documentation was focused on it for structural reasons.

Methodology

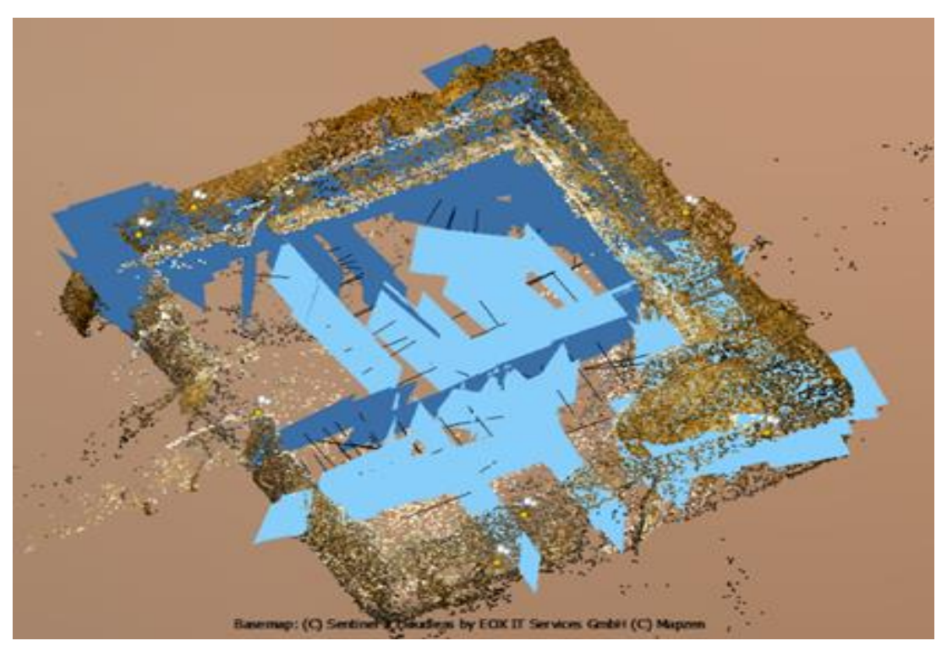
This study evaluates the accuracy of three photogrammetric acquisition methods, each of which differs in the camera used and the acquisition approach: a "free handheld" frame camera (Dataset 1 – Nikon D780), a "standard" photogrammetric frame camera (Dataset 2 – Canon 550D), and a "360°" multi-lens camera (Dataset 3 - Xphase pro X2) at arbitrary positions. It is worth mentioning that every "360°" stitched panorama offers 134MP resolution, produced by the combination of 25 cameras with 8MP resolution each. Once the acquisition of the three photogrammetric datasets was completed, their process was followed in Agisoft Metashape software to generate dense point clouds. Subsequently, statistical/key metrics comparisons were conducted in CloudCompare (CC).

Dataset 1 – Nikon D780

The goal was rapid photo acquisition with maximum coverage, ensuring overlaps for SfM and adaptability to geometry. Operator expertise was crucial. 26 of 74 photos were manually selected for dense point cloud generation.

Dataset 2 – Canon 550D

The acquisition was done using two self-calibrated zoom lenses (10-18mm and 18-135mm) with a "traditional" fixed-base setup with 80% overlap. 66 of 136 photos were manually selected for dense point cloud generation.



Dataset 3 – Xphase pro X2

The 360 images were acquired 1 year later than the other 2 datasets, without targets, and were co-registered with the Nikon images for bundle adjustment. 20 of 114 photos were manually selected for dense point cloud generation.

Datasets and equipment used information

Dataset	Reference	Dataset 1	Dataset 2	Dataset 3
Instrument	Faro Focus S70 TLS	Nikon D780, 20mm prime lens	Canon 550D, 10-18 & 18-135mm zoom lenses	XPhase pro X2
Sensor resolution	1.5mm/10 m	Full frame, 24.5 MP, 6μm pixel	APS-C, 18MP, 4μm pixel	25 x 8MP, 134MP stiched panorama, 1.4μm pixel
Real focal length [mm]		20	Variable 10-18	3.85
Number of scans/images for Tomb 7	29 scans	74	136	114
Number of images used for the wall	-	26	66	20
Survey period	June 2023	June 2023	June 2023	July 2024
Acquisition time for Tomb 7 [min]	240	23 (wall only)	240	133
Average time per photo [min]	-	0.9	1.8	1.2

Processing parameters for the datasets

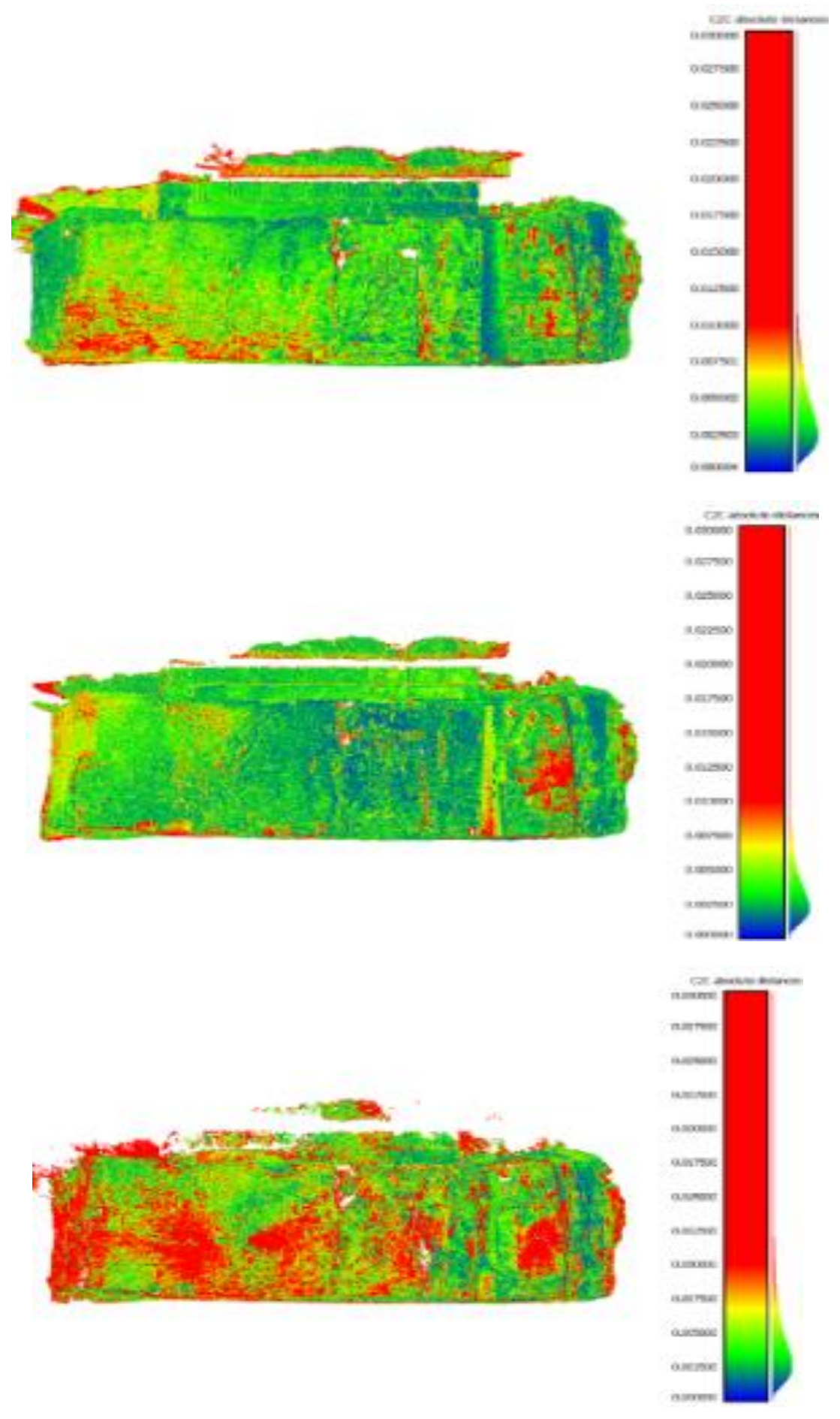
Dataset	Dataset 1	Dataset 2	Dataset 3
Number of photos	26	66	20
Total Mp	624	1188	2600
Average distance to object [m]	4.5	4	1.5
Average GSD [mm]	2	2	1
Tie points in 3D [K]	67	99	55
Average tie point multiplicity	3.5	4.5	3.7
Reprojection error [pixels]	0.66	1.00	2.27
Number of GCPs	6	7	6
Control point RMS (3D Total) [m]	0.005	0.006	0.005
Control points reprojection error [pixels]	0.35	1.2	0.5
Final clipped PC [Mpoints]	8.2	29.9	40.7

Metrics results of datasets comparison

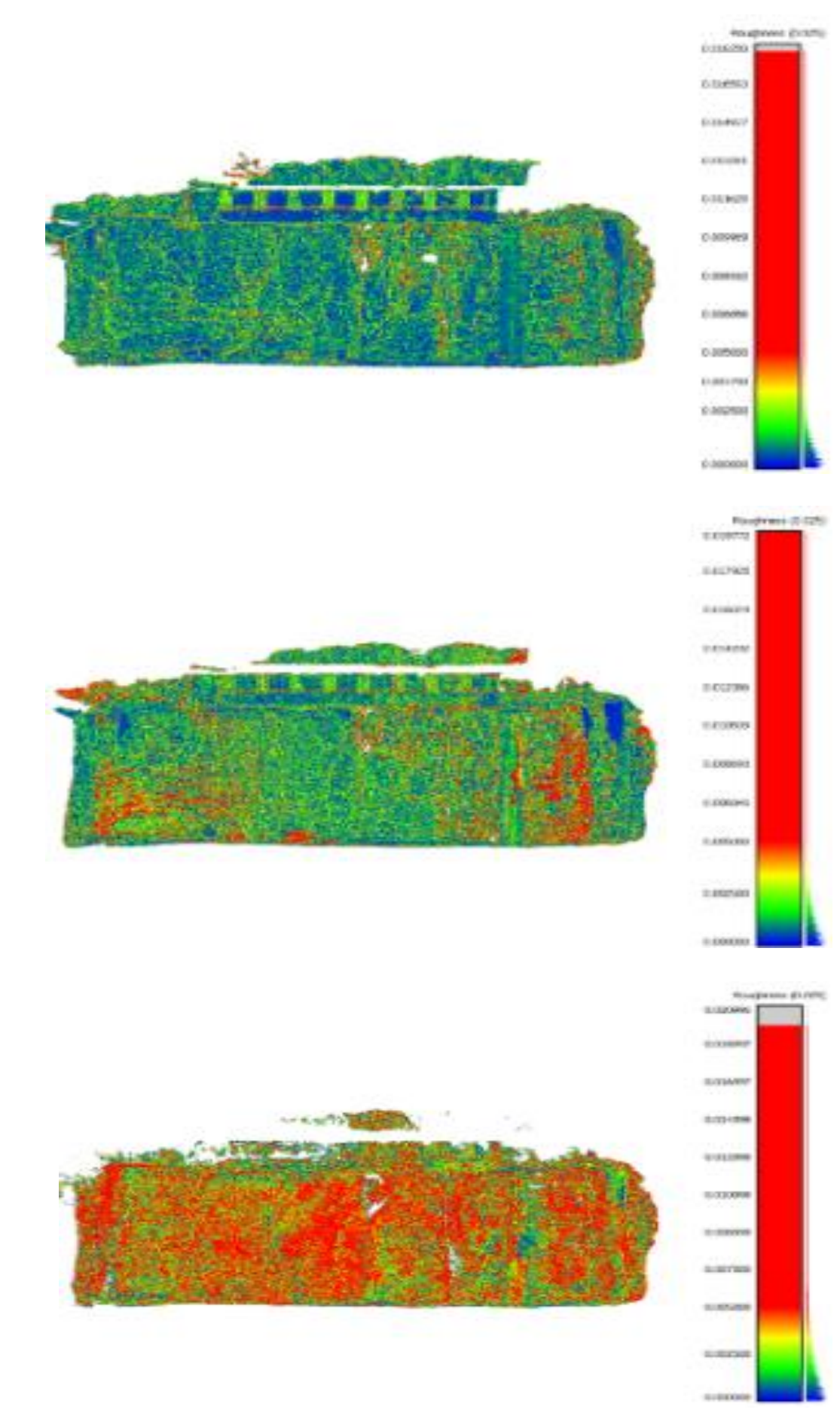
Metrics	TLS data	Dataset 1	Dataset 2	Dataset 3
Final clipped point cloud [Mpoints]	72.6	8.2	29.9	40.7
Mean discrepancy [mm]	-	4.8	4.6	5.7
Discrepancy std. dev. [mm]	-	3.6	3.0	5.6
RMS [mm]	-	6.0	5.5	8.0
Roughness at 1.0 cm [mm]	1.1	0.5	0.7	1.1
Roughness at 2.5 cm [mm]	2.0	1.2	1.6	2.3
Surface Density at 2.5 cm [points/m^2]	1995K	70K	256K	347K

Metrics results - Graphical comparison

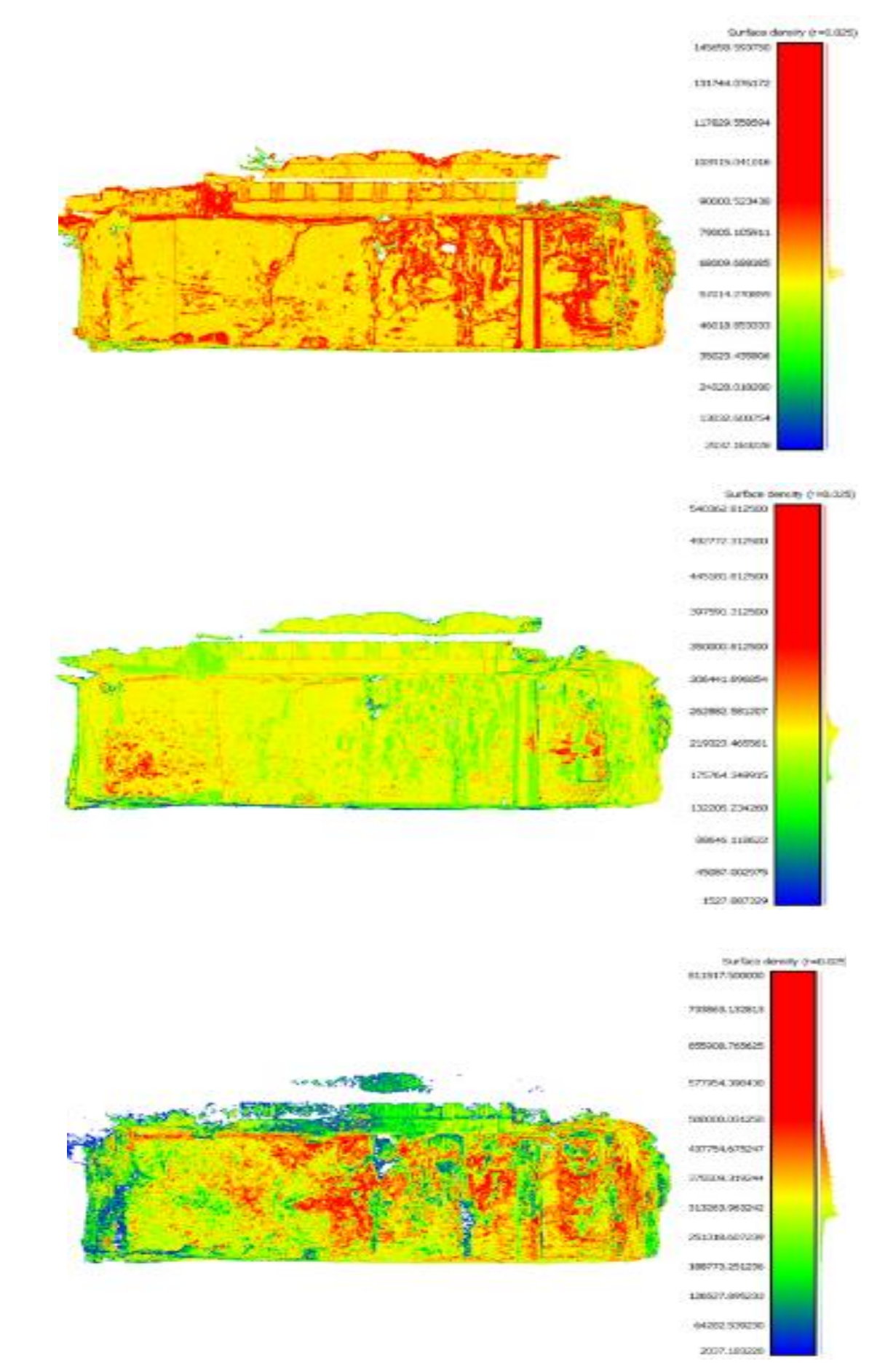
Unsigned Cloud-to-Cloud Distance
D1, D2, D3



Roughness (2.5 cm)
D1, D2, D3



Surface Density (2.5 cm)
D1, D2, D3



Discussion

This comparison evaluates the "free handheld" (D1) and "standard" (D2) practices against "360°" (D3) cameras for photogrammetric data acquisition, focusing on accuracy, practicality, and cost.

The handheld method exhibits lower reprojection errors compared to standard practice. However, this is likely due to the superior camera-lens combination used (full-frame with a prime lens vs. APS-C with a zoom lens) rather than the acquisition method itself. While the handheld method is faster, it provides less consistent results, posing a risk to accuracy. Conversely, standard practice ensures uniform, high-quality data but requires more time. A combined approach could balance these strengths, enhancing detail in specific areas while maintaining uniformity, albeit at the cost of increased acquisition time.

The 360° camera, significantly cheaper (less than one-third the cost of the full-frame rig), displayed the highest reprojection errors and noisiest point cloud. These issues stem from uncontrolled stitching of images into panoramas, which cannot be fully corrected during bundle adjustment. While the final 3D reconstruction benefit from high GSD and total Mpixels, the RMS error is at least 33% worse than frame cameras. Modeling lens distortions using a fixed rig of independent cameras could improve its performance.

The 360° camera excels in confined spaces, offering advantages like uniform data capture, a streamlined pipeline, and the ability to generate textured 3D meshes essential for structural analysis, such as the width of cracks. However, its value diminishes in open spaces, where sky coverage impacts alignment and unnecessarily increases data storage and processing. Despite these limitations, the 360° camera provides precise, cost-effective results suitable for projects with spatial constraints or tight budgets. Further research into its use as a rig of independent cameras could enhance its potential for photogrammetry, particularly for structural monitoring in cultural heritage settings.

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