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Evolution of the 3D Documentation of the Necropolis of Qubbet el-Hawa (Aswan, Egypt) Based on Data Fusion

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Abstract

This study describes the evolution of workflows implemented over six campaigns for the complete graphical documentation of an Egyptian necropolis. The primary objective was to enhance data acquisition efficiency while ensuring a high geometric and radiometric quality. The methodology integrates several geomatic techniques: terrestrial laser scanning (TLS), close-range photogrammetry (CRP), and spherical photogrammetry (SP). It emphasizes their combined use, taking advantage of their respective strengths to achieve this goal. The approach adapted to site characteristics, instrument availability, and concurrent archaeological activities. We also analysed the impact of reducing control points from surveying, given its significant effect on field tasks. The approach addresses external and internal scenes (tombs) individually. Initially, external areas were documented solely with CRP, but TLS and SP were incorporated in subsequent campaigns. Conversely, burial structures were initially documented using CRP and TLS, with SP (both static and mobile) later employed for texturing. The results demonstrate the advantages of data fusion across multiple techniques, considering both quality and acquisition efficiency. In conclusion, TLS primarily focuses on 3D model geometry, while CRP and SP concentrate on texture. This combined approach has proven essential for short field campaigns, especially when coinciding with archaeological excavations and facing other difficulties like existing material within tombs or the presence of tourists.

1. Introduction

Heritage documentation has undergone significant evolution in recent years. The development of new geomatic techniques and advancements in hardware and software applications have led to a breakthrough in this field. This evolution is particularly evident in long-standing archaeological projects, where graphic documentation progresses through successive campaigns over years or even decades. The inclusion of new techniques often aims to improve acquisition and processing efficiency, obtain higher-quality products, and enable novel analyses based on spatial data. Despite the wide availability of data acquisition systems currently on the market, their use is sometimes limited in certain projects due to specific site-related issues or other restrictions, such as the absence of administrative permissions for Unmanned Aerial Vehicles (UAVs). In such cases, alternative methods that can ensure a certain level of efficiency and data quality must be considered.

In Egyptian archaeological projects, fieldwork typically involves numerous tasks carried out over short periods of time by various researchers during archaeological campaigns. Consequently, these simultaneous works (e.g. excavations, restorations, etc.) complicate geomatics tasks, as data acquisition often requires other activities to pause. Furthermore, all tools and archaeological material must be removed from the scenes to minimize occlusions, only to be returned after the capture is completed. This necessitates that acquisition be as efficient as possible, while still ensuring full coverage and data quality, as this task often cannot be repeated. In this context, employing several geomatic techniques can reduce data acquisition time, while their combined application ensures survey completeness across the entire scene and enhances data quality by allowing for cross-validation of results and deviations.

During the last decades, several authors have described approaches for developing geomatic studies of these sites (Nabil et al., 2013; Pérez-García et al., 2019a; Elbshbeshi et al., 2023), even in inaccessible spaces (Pérez-García et al., 2019b). These methods can be based on data obtained from a single technique, such as Light Detection and Ranging (LiDAR) and, more specifically, Terrestrial Laser Scanning (TLS) (Echeverría et al., 2019), or photogrammetry (Mandelli et al., 2021). Alternatively, they can leverage the fusion of data obtained from multiple techniques (e.g. Mozas et al., 2020; Sykora et al., 2023; Lang et al., 2023). The combined use of TLS and photogrammetry has been extended to a large number of applications, including complex archaeological sites where the implementation of several techniques is widely justified. Multiple studies (Kadobayashi et al., 2004; Guarnieri et al., 2006; Lerma et al., 2010; Alshawabkeh et al., 2021) have demonstrated advantages when combining LiDAR and photogrammetry, given the potential to exploit each technique’s strengths. In this regard, some studies have described the advantages and disadvantages of these techniques when applied to heritage documentation (Hassan and Fritsch, 2019). In this context, the application becomes more complicated in cases involving sites with challenging geometrical characteristics, difficult location and accessibility, or other environmental aspects. These cases are often categorized as complex scenes (Pérez et al., 2024). Recently, imaginative solutions have been developed to survey them. These approaches are primarily based on employing multiple sensors and acquisition techniques to facilitate complete scene coverage, thereby improving the efficiency of data acquisition and processing. For example, in photogrammetry, increasing the field of view (FoV) of sensors provides greater coverage per image and, consequently, reduces the number of images needed to cover a scene. In this context, several recent studies have demonstrated the feasibility of using wide-angle lenses (Martínez et al., 2013), fisheye lenses (Mandelli et al., 2017) and 360-degree cameras (Barazzetti et al., 2017). Notably, Pérez et al. (2024) described the efficiency

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advantages of using 360-degree cameras based on spherical photogrammetry (Fangi, 2007), whether using fisheye images or spherical/panoramic images. For fisheye images, Pérez et al. (2024) suggested using extrinsic calibration of 360-degree cameras to define constraints between fisheye sensors (Perfetti et al., 2018), thereby improving orientation procedures and minimizing the need for ground control points (GCPs). Other approaches related to acquisition efficiency focus on real-time capturing. In the case of photogrammetry, the recent application of videogrammetry (Torresani and Remondino, 2019) is noteworthy, both based on frame selection (Alsadik et al., 2015) and the integration of video streams in Mobile Mapping Systems (MMS) (Debeunne, 2020). In the former case, the frame selection procedure is fundamental, as data acquisition often provides lower-resolution images compared to still captures, along with blur effects, and redundant overlaps (Sun and Zhang, 2019).

1.1 The Necropolis of Qubbet el-Hawa

The necropolis of Qubbet el-Hawa (Aswan, Egypt) consists of over one hundred burial structures (hypogea) excavated into a hill on the west bank of the Nile River. Its privileged location, adjacent to the modern city of Aswan, is attributed, among other reasons, to its proximity to Elephantine Island, where the capital of the southern region of ancient Egypt was established (Figure 1a). The Necropolis is distributed along the hill at various elevations, with a main archaeological area of approximately 1.2 hectares (Figure 1b). This funerary site was primarily used during the Old Kingdom and the Middle Kingdom to bury prominent members of Elephantine society, such as governors, their relatives and households (Jiménez-Serrano, 2023). However, most burial structures (coded with the prefix QH) were subsequently reused, even for other purposes (e.g., as a monastery in the medieval period). Most tombs are simple in construction, featuring a single niche, while others have a complex structure. In these cases, tombs are composed of several spaces depending on the style and period of construction. Generally, complex Middle Kingdom structures include an external courtyard (e.g. QH36 in Figure 1c) and several rock-cut spaces, divided into two zones: public and private (or burial). The public zone typically comprises a hall of pillars, a corridor, an offering chamber, and a sanctuary or chapel. The private area includes several corridors, a vertical shaft (e.g., up to 14 metres in QH33), a main burial chamber, and multiple niches. These structures are therefore quite large, reaching lengths of over 30 metres inside the hill (e.g., QH31 is 32 metres long). Public areas are characterized by vertical, polished walls with a high level of flatness, some also decorated with paintings and inscriptions. In contrast, private areas often feature raw finishes with chisel marks and exhibit lesser geometrical and artistic interest (Mozas et al., 2023).

The University of Jaén (Spain) has conducted an archaeological project at this site since 2008, focusing on the study and documentation of several Middle Kingdom burial structures. However, the geomatic team has only participated in the latest six campaigns (from 2017 to 2024), documenting both the topographic surface and over ten hypogea of interest for the project. This documentation has included obtaining 3D models of the exterior and interior spaces, digital elevation models (DEMs) and orthoimages of some elements of interest. The total extension of the hill (about 9 hectares), the complex structure of most tombs (characterized by multiple and narrow spaces), instrument availability, restrictions (e.g., on UAVs), and other issues conditioned the application of geomatics techniques to document this site. Furthermore, the topography is dynamic due to two active archaeological teams working in different areas (among other causes, such as the sand movement caused by the wind). Archaeological work involves removing sand and debris from areas of interest, thereby updating the topographic surface of these structures. Additionally, the site is continuously visited by tourists, which imposes limitations on acquisition time in areas accessible for their tour.

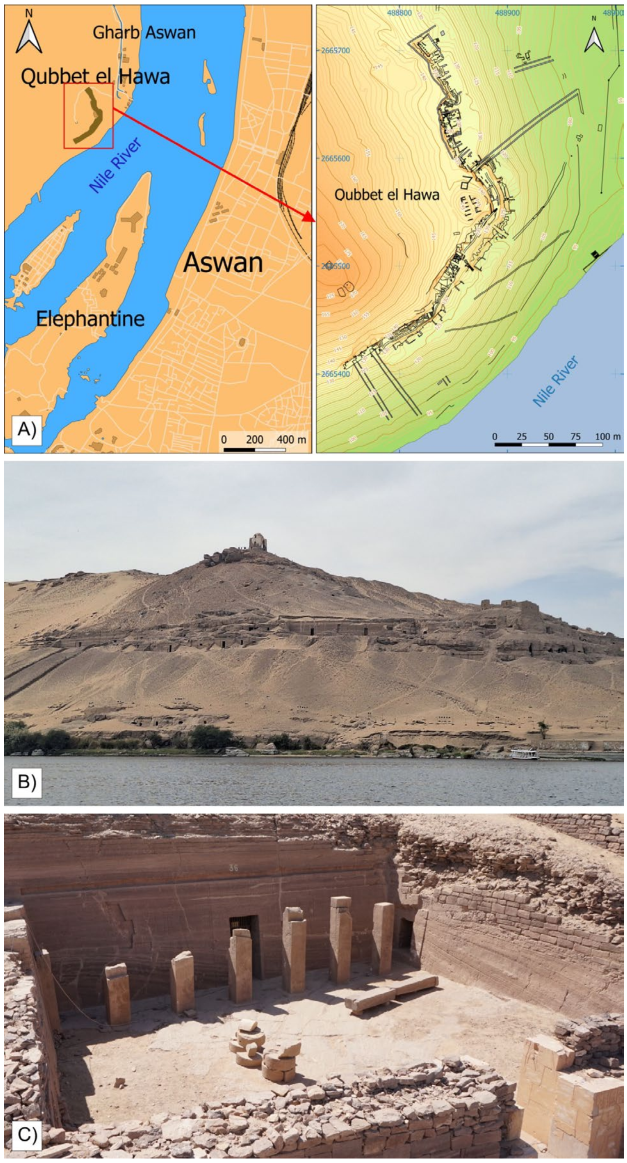

Figure 1. Necropolis of Qubbet el-Hawa: a) Location; b) general view of the hill; c) detailed view of the courtyard of QH36.

1.2 Objectives

The objectives of this study were to obtain complete graphic documentation of the site, with special attention to the archaeological works carried out during each campaign, and to improve the efficiency of data acquisition by guaranteeing a certain level of geometric and radiometric quality. Acquisition time is critical in areas with ongoing archaeological works or visited by tourists. To achieve these goals, several techniques have been applied following a specific methodology that reflects their evolution and adaptation to the site’s circumstances. The document is structured as follows: First, we present the geomatic techniques applied at this site and their evolution throughout the survey campaigns. Second, we provide a summary of the main results obtained from their application justifying the evolution implemented and highlighting the advantages of data fusion. Finally, the main conclusions are described.

2. Methodology and application

The methodology implemented in this study is summarized in Figure 2 and described in this section by geomatic technique. It is important to note that the application of these techniques varied across campaigns due to the evolving nature of the geomatic work, instrument availability, and the scene's characteristics. In this context, the importance of the scene, which sometimes includes significant artifacts (e.g., pottery, coffins, wooden models of boats), conditioned the requirements of the products to be obtained. Thus, these aspects defined the level of detail (geometric and texture resolutions) to be achieved. For example, public spaces typically demanded greater requisites than private areas. However, a specific burial niche within a private area might contain a coffin, necessitating detailed surveying. Generally, high detail is required in archaeological areas outside the tombs and in their public areas, while exterior non-archaeological areas and private areas required lower detail, although the presence of significant artifacts could change this assumption. Further details on the application are provided in section 2.5.

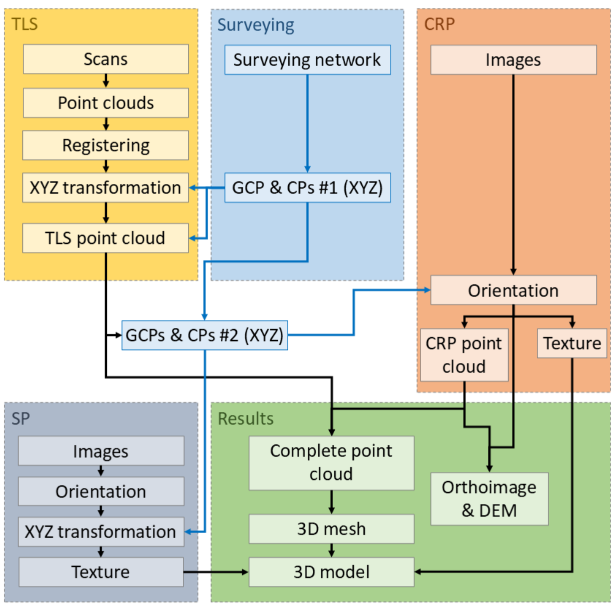

Figure 2. Methodology developed in this study.

2.1 Surveying

Surveying work was conducted to establish networks, determining topographic points distributed throughout both the external area of the necropolis and inside the tombs. The main surveying network was initially developed along the necropolis (exterior) and measured using a Global Navigation Satellite System (GNSS) (Leica System 1200) and a total station (Leica TCR407) (Figure 3a). Subsequently, several secondary surveying networks were materialized and measured inside the tombs using a total station. All surveying networks were referenced to the same Coordinate Reference System (CRS) to ensure a consistent framework for all surveys, regardless of their location outside or inside the tombs. Finally, we also obtained several Ground Control Points (GCPs) and checkpoints (CPs) from these topographical points composing the surveying networks. These were used to georeference and assess the quality of products determined with other techniques and were materialized using targets, and were well-distributed throughout the scene.

Figure 3. Images of the application: a) Surveying network (exterior); b) TLS and SP (exterior); c) CRP from a mast (exterior); d) TLS (interior QH36); e) CRP (interior QH36); f) SP from a mast (interior QH36).

2.2 Terrestrial laser scanning:

TLS surveys were also performed outdoors and indoors using a Faro Focus X130 scanner (Figure 3b and Figure 3d). The primary objective was to acquire the geometry of the scene through a comprehensive point cloud composed of several individual point clouds obtained from a set of scan stations. These stations were well-distributed over the scene, considering the topographic surface (exterior) or the tomb's structure (interior), to ensure maximum coverage and avoid occlusions. Adjacent scans were also positioned with significant overlap to facilitate the relative registration of the point clouds (Figure 4a). We selected a density of 7 millimetres at 10 metres and performed scans without colour registration, as textures would be obtained from photogrammetry. The definitive point cloud of each scene was georeferenced using several GCPs through a 3D transformation. Some CPs were also checked to assess the positional accuracy of the products. These GCPs and CPs were obtained from the surveying network (GCP & CPs #1 in Figure 2). Once the point cloud was determined, it was used to ascertain the coordinates of additional materialized targets, which facilitated the georeferencing of photogrammetric products (GCP & CPs #2 in Figure 2). This process significantly reduces the reliance on GCPs and CPs obtained solely through surveying techniques.

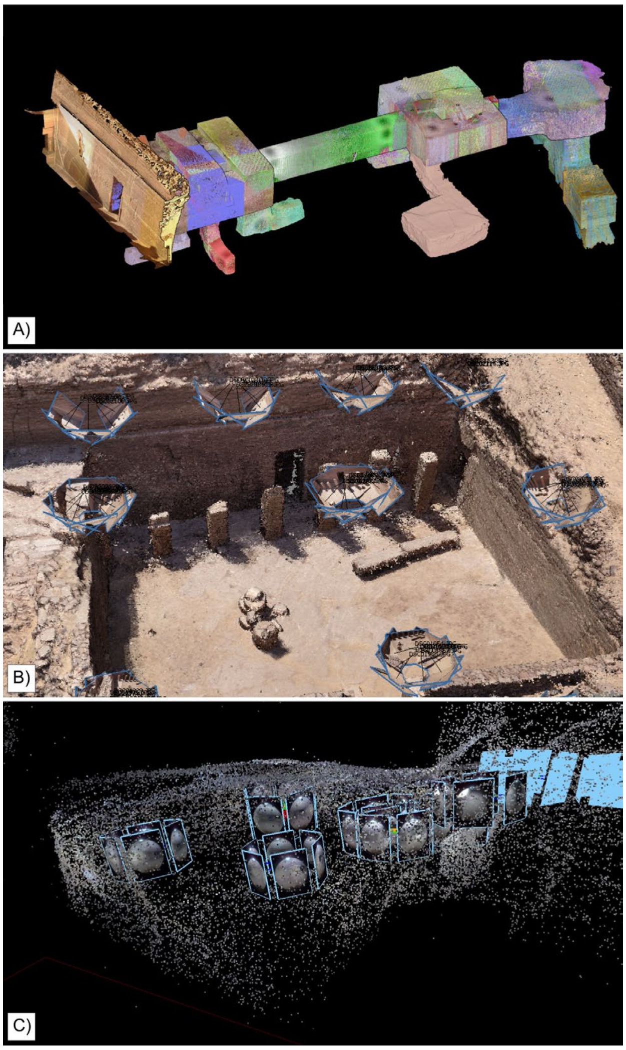

Figure 4. Examples of the application carried out in QH36: a) TLS: point cloud registration; b) CRP: oriented images in the courtyard; c) SP: oriented fisheye images in a burial chamber.

2.3 Close range photogrammetry

CRP was performed using a conventional camera (Sony Alpha 6000), following the recommendations of the CIPA for photogrammetric documentation (known as the 3x3 rules) (Waldhäusl et al., 2013). This involves capturing convergent photographs in a ‘ring’ around the subject with at least 60% overlap. To achieve high efficiency in image acquisition, we implemented various systems based on different accessories depending on the survey context. In exterior areas, for instance, we used a mast up to 6 metres (Figure 3c) to elevate the viewpoint in locations where the topographic surface caused occlusions (Pérez-Garcia et al., 2019a). Acquisition involved capturing eight images from each mast station covering 360 degrees. Convergent images were obtained from several adjacent stations (Figure 4b). The mast was also used in some specific cases related to tombs, particularly to document inaccessible spaces, such as niches (Pérez-Garcia et al., 2019b). Using a mast naturally necessitates incorporating a remote control for the camera.

Another system implemented in internal areas addressed the radiometric quality of images. Unfortunately, tombs often had poor illumination conditions. This led to the installation of an LED illumination system mounted alongside the camera (Figure 3e), aiming to achieve homogeneous conditions and ensure a certain radiometric quality. Capture in indoor scenes was quite similar to the exterior, focusing on obtaining convergent images throughout the scene. CRP was mainly used for texturing meshes, although point clouds obtained during photogrammetric processing were also employed to determine the geometry in cases where TLS was not implemented. Furthermore, CRP was employed to supplement TLS-generated point clouds in regions affected by occlusions, thereby addressing data gaps. GCPs were used to georeference CRP products (point cloud, orthoimages, DEMs, 3D models, etc.) and CPs were used to assess their positional quality. These GCPs and CPs were either measured using surveying techniques or extracted from the TLS point cloud (GCP & CPs #2 in Figure 2). CRP results included textures for 3D model generation, DEMs and orthoimages.

2.4 Spherical photogrammetry

SP was primarily implemented to improve image acquisition and facilitate photogrammetric survey in complex scenes (Pérez et al., 2024). For this study, we used a Kandao Obsidian Go 360-degree multicamera, which consists of six sensors with fisheye lenses distributed at 60-degree intervals. The camera allowed us to obtain both photographs and videos. Thus, images could be acquired in two modes: stationing at a fixed location or moving along a planned trajectory. In the former case, we obtained six fisheye images per station, with stations well-distributed along the scene to ensure full coverage. In the latter case, we obtained six synchronized videos, from which sets of six images were extracted at specific timestamps. While video acquisition increases efficiency, it presents some challenges related to the lower-resolution images, blur effects, and redundant overlaps. In all cases, the camera was fully calibrated to obtain its extrinsic parameters. These parameters can then be used to define constraints as a function of the distance between sensors (scale bars). This facilitates relative orientation (Figure 4c) and reduces the necessity of GCPs to only those needed for a 3D rigid transformation (a minimum of 3 points). GCPs and CPs were selected from the surveying and TLS data (GCP & CPs #2 in Figure 2).

SP was employed in both exterior scenes and inside the tombs. In external scenes, the camera was mounted on a mast up to 4 metres, achieving greater coverage of the topographic surface (Figure 3b). In indoor scenes, an illumination system based on a LED lamp was mounted on the camera (Figure 3f). The camera was also mounted on a mast to survey vertical shafts. The output of this technique includes a texture to be added to the final point cloud to obtain a 3D model.

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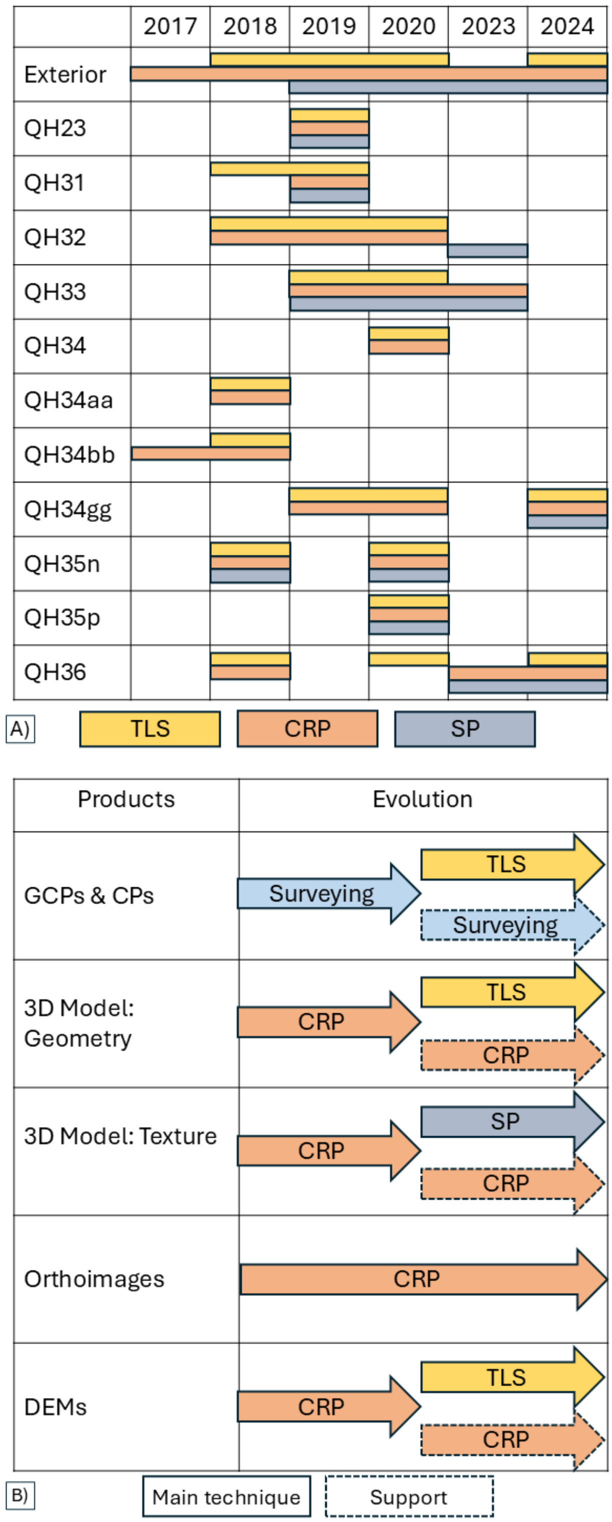

Figure 5. Geomatic techniques applied in this study: a) temporal distribution by campaigns and scenes; b) evolution by product.

2.5 Application and evolution of geomatic works

The application of these techniques was implemented gradually across campaigns from 2017 to 2024 (Figure 5a), incorporating improvements throughout this period. The first campaign (2017) focused solely on the exterior, utilizing CRP on a mast to obtain more than 2400 images. These were processed by zones to generate several orthoimages, DTMs, and a 3D model (Pérez-Garcia et al., 2019a). Subsequently, CRP was applied inside the tombs. From 2018 to 2024 (excluding 2023), TLS was primarily used to determine the geometry of the scenes, thereby reducing the reliance on CRP for this purpose (Mozas-Calvache et al., 2020). Consequently, CRP has focused on obtaining scene texture during the latest campaigns. SP has been applied in both exterior and interior scenes since 2018 for texturing. In 2024, we tested mobile acquisition using videogrammetry instead of still images to further improve efficiency.

The evolution in the application of these techniques primarily aimed for higher acquisition efficiency but can also be justified by other circumstances (e.g. instrument availability). Considering the product to be obtained, Figure 5b illustrates this evolution, taking into account the main technique applied in each case and those used for support. Generally, we developed surveying networks to determine the coordinates of GCPs and CPs both in the exterior and the interior of the tombs. However, we endeavoured to reduce these time-consuming tasks. Thus, in the latest campaigns, georeferenced TLS point clouds have also been used to determine GCPs and CPs, decreasing the need for those obtained from traditional surveying. This represents an important improvement in acquisition workflows, as it eliminates the need to extend the surveying networks to the latest areas of the tombs. Regarding 3D models, they were initially based on CRP; however, they are currently based on TLS for geometry acquisition and SP for texturing. Nevertheless, the presence of gaps in TLS data often required CRP support to complete the geometry and for texturing, particularly where high detail was required. For orthoimages, CRP has consistently been used due to the radiometric quality and resolution demanded by the project. However, we have improved its application by considering advancements in illumination systems. Finally, DEMs are derived from the geometry. Therefore, their evolution closely parallels that of the geometric component of 3D models (Figure 5b).

3. Results and discussion

After six campaigns, we have obtained a large number of results and products to document the site, such as 3D models of both interior (Figure 6a) and exterior scenes (Figure 6b), DEMs, and orthoimages (Figure 6c). These products have also enabled the documentation of archaeological work evolution both during individual campaigns and across multiple campaigns. Figure 6d shows a comparison between 3D models obtained from the QH34 area from 2017 to 2024 and the evolution of the geomatic techniques implemented considering geometry and texture. This example clearly demonstrates the evolution of our application, as only CRP was utilized in 2017, while TLS and SP were employed in 2024. The improvement in acquisition efficiency and product quality is evident. In general, all products obtained in this study were geometrically assessed using independent CPs, yielding accuracies of approximately 3 centimetres (Pérez et al., 2019a; Mozas et al., 2020; Pérez et al., 2024). For TLS registration, the average residuals with respect to GCPs obtained from surveying were about 4 millimetres (with a typical deviation of 3 millimetres). This justifies the use of GCPs extracted from TLS data, minimizing the need for those obtained from a total station. Another significant improvement relates to the use of SP for texturing, which offers clear advantages over CRP in terms of acquisition time. At a single photographic station, we obtained six images simultaneously with extensive coverage, as opposed to a single image with reduced coverage, thus avoiding overlap issues. Consequently, we estimate an acquisition time reduction of at least sixfold.

Conversely, SP yields lower resolution and poorer radiometry, as the illumination level depends on the distance from the LED system to the object. In a set of images covering 360 degrees, these distances exhibit more variability compared to cases with lower FoV. Therefore, this issue is more easily controlled with CRP by adjusting illumination intensity based on object distance or by setting the camera sensor's sensitivity (ISO parameter) to automatic. Thus, SP's use in interior scenes is justified when texture does not require a high level of detail, whereas CRP is suitable for areas demanding greater resolution and radiometric quality (e.g., inscriptions shown in Figure 6c). The use of SP in mobile mode (videogrammetry) is particularly advantageous in external scenes, as it minimizes acquisition time. Employing a mast to elevate the camera allowed us to avoid occlusions caused by the topographic surface. At this moment, our experience does not suggest using this approach in internal scenes due to illumination difficulties that cause problems such as blur effects.

In this study, we highlight the methodological changes implemented across campaigns as the main result, which have significantly improved acquisition efficiency and product quality. These results are based on the evolving application of several techniques and their data fusion. The evolution developed during six campaigns has led to a clear workflow based on these aspects: geometry is mainly obtained from TLS (supported by CRP in complex areas) and texture generally from SP, with CRP reserved for areas requiring high detail. Additionally, the use of relatively registered TLS point clouds greatly reduces the need for total station measurements, as most targets can be measured from the final TLS point cloud. With this technique, we can increase the number of GCPs and CPs, thereby improving the quality of photogrammetric orientation. In the case of SP, we improve the orientation procedure and reduce the number of necessary targets by utilizing fisheye images and camera extrinsic calibration parameters, which enable the inclusion of scale bars as constraints for orientation procedures. Acquisition time is minimized using TLS and SP under these conditions, with GCPs primarily used for georeferencing purposes through 3D rigid transformations.

Based on the experience gained from this project, Table 1 proposes an implementation strategy for geomatic techniques, considering common scene features encountered at such sites. We categorize three scene classes (exterior, public and private areas) and two levels of detail (high and low). Simple structures composed of a vertical shaft and a niche are considered private areas. The recommendations in Table 1 are general; the selection of the level of detail (high or low) should primarily consider the scene's significance and the presence of inscriptions, decorations, artifacts (e.g., coffins), or other specific requirements (e.g., performing a geometrical analysis, as described in Mozas et al., 2023). These specific cases should be treated as exceptions, mandating surveying with high resolutions to obtain finer geometry and texture.

Scene	Detail	Geometry	Texture
Exterior	High	TLS & CRP	CRP / SP
Exterior	Low	TLS & SP (video)	SP (video)
Public area	High	TLS & CRP	CRP
Public area	Low	TLS & CRP	SP
Private area	High	TLS & CRP	CRP
Private area	Low	TLS & SP	SP

Table 1. Recommendations for applying the methodology considering the scene

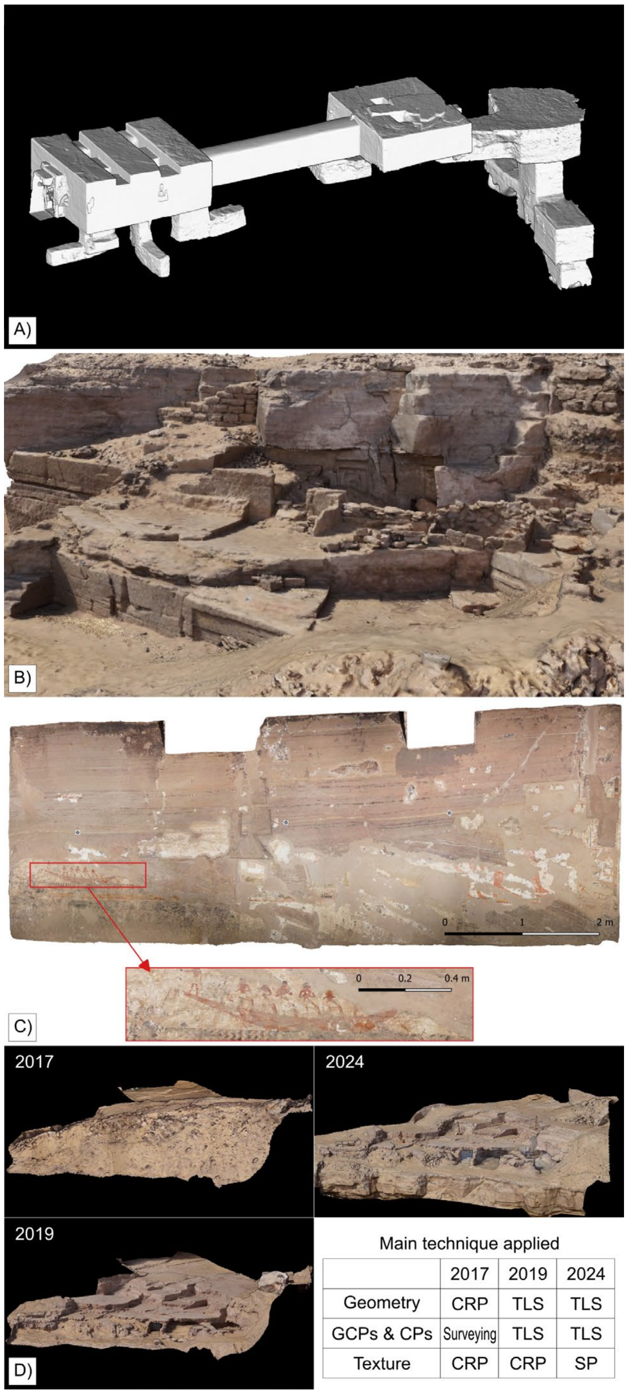

Figure 6. Examples of the results obtained: a) 3D mesh of QH36; b) 3D model of the exterior area next to QH34cc; c) orthoimage of the northern wall of the hall of pillars (QH36); d) evolution of the documentation carried out in different campaigns (exterior area next to QH34).

4. Conclusions

In this study, we have described the evolution of the geomatic methodology implemented to document the necropolis of Qubbet el-Hawa over six campaigns. This methodological evolution has demonstrated an improvement in acquisition efficiency, proving essential for short field campaigns that often coincide with archaeological works and the presence of tourists.

The evolution includes the synergistic use of several techniques, leveraging their respective potentials to reduce acquisition and processing time. Our approach considers data fusion between techniques based on specific premises. Thus, the results and field experience suggest TLS for obtaining the scene's geometry, supported by CRP in cases where TLS coverage is incomplete (e.g., in complex areas or with occlusions). The TLS point cloud is also utilized to obtain the coordinates of GCPs and CPs for georeferencing CRP and SP products, significantly reducing the number of points obtained from traditional surveying. This represents a substantial improvement in accuracy and efficiency. Furthermore, the texture of the 3D models is obtained from both CRP and SP. CRP is used when a specific level of detail and radiometric quality is required. SP, conversely, is more effective when fine detail is less critical, offering the possibility to improve acquisition efficiency by more than 6 times compared to CRP. A more significant improvement is obtained when using SP in mobile capturing mode (videogrammetry). Unfortunately, our results primarily suggest this approach for external surveys due to abundant blur effects caused by challenging illumination conditions in internal scenes.

In future, our efforts will continue to focus on enhancing efficiency through the inclusion of low-cost mobile mapping systems and the refinement of the current methodology based on TLS, CRP and SP. Improving illumination systems remains another key area to address, especially when employing videogrammetry in suboptimal conditions.

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