ANALYSIS OF WALLS AND PILLARS OF THE HYPOSTYLE HALL AT THE QH31 TOMB (ASWAN, EGYPT) BASED ON 3D MODELS

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ABSTRACT:

This study describes the methodology developed and the results obtained about the geometric behaviour of walls and pillars of one of the most prominent rock-cut funerary structures of the Middle Kingdom period located in the Necropolis of Qubbet el-Hawa. More specifically, we selected the hypostyle hall of the QH31 hypogeum, one of the greatest in the Necropolis, to apply this methodology. The main objective is related to obtaining geometrical aspects of walls and pillars in order to understand the constructive procedure carried out almost four millennia ago. The methodology was based on photogrammetric and TLS surveys that allowed us to obtain a complete combined 3D model of the structure, geometrically contrasted and with real texture. From this product we obtained a high density point cloud, where some planes were fitted considering the walls and pillars that defined the structure. These planes were characterized by their normal vectors, which were used to analyse several geometric aspects such as inclinations, parallelism and perpendicularity. As results, we have obtained important information about the level of accuracy of the constructive procedure carried out by the ancient Egyptians. In this sense, the values obtained allow us to suggest and confirm several hypotheses about the construction of this hypogeum. The proposed methodology has demonstrated its feasibility for determining these geometric aspects of funerary structures through the analysis of the fitted planes obtained from the 3D model.

1. INTRODUCTION

3D documentation of archaeological sites is currently undergoing a great expansion thanks to the development and availability of geomatic techniques and sensors that facilitate its application even in complex scenes (Martínez et al., 2013; Farella, 2016; Fiorillo et al., 2016; Barazzeti et al., 2017; Perfetti et al., 2017; Pérez-García et al., 2019). This is the case with Egyptian funerary structures (e.g. hypogea) where several halls, corridors, chambers and vertical shafts make surveying tasks difficult due to the presence of narrow spaces, poor illumination conditions, etc. In addition to these difficulties, sometimes the structure and its contents condition a quick documentation without access to the space, being necessary the use of remotely-controlled devices (Pérez-García et al., 2019). Considering the current capabilities, we should consider using two geomatic techniques to develop this documentation based on photogrammetry and Terrestrial Laser Scanning (TLS). In this context, Hassani (2015) described the advantages and disadvantages of their application for the documentation of cultural heritage. However, the use of both is not incompatible. In fact, several studies have demonstrated the advantages of integrating both techniques (Kadobayashi et al., 2004; Alshawabkeh and Haala, 2004; Guarnieri et al., 2006; Grussenmeyer et al., 2008), even in the cases of Egyptian tombs (Ahmon, 2004; Nabil et al., 2013; Lima and Vergauwen, 2018; Mozas-Calvache et al., 2020). In general, photogrammetry allows us to obtain 3D documentation that includes real textures in addition to other products, such as Digital Elevation Models (DEMs) and orthoimages which can be used to analyse archaeological and architectural aspects of the tomb. On the other hand, TLS allows us to obtain a quick documentation of the structure of the tomb, although the use of scanners supposes an increase in cost compared to low-cost photogrammetry.

Efficiency in data acquisition supposes an important aspect to be considered in this type of study, due to the time constraints that commonly affect projects in Egypt and the possible existence of other works, the presence of tourists, etc., which can greatly condition the data capture tasks. In this context Mozas-Calvache et al. (2020) demonstrated the improvement of acquisition efficiency by dividing the data obtained from both techniques, taking advantage of their particular characteristics. Thus, the 3D documentation obtained in their study was a result of the integration of both data. In this sense, geometry determination was mainly based on TLS and photogrammetry was focused on obtaining real textures and other products (DEMs and orthoimages), and completing geometry in the case of gaps left in the TLS survey. To improve acquisition efficiency there is currently the possibility of using mobile-mapping systems (MMS) such as those based on simultaneous localization and mapping (SLAM), which calculate the trajectory of the system using point clouds or images (LiDAR SLAM and Visual SLAM). These systems allow obtaining 3D data, achieving accuracies of several centimetres (Di Stefano et al., 2021) in a few minutes.

The geometric analysis of funerary structures in Egypt has traditionally been based on plans and sections obtained by simple measurements and surveying techniques (Rossi, 2001; Martinez-Hermoso et al., 2015). However, we can take advantage of the possibility of using the 3D documentation

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obtained using the current geomatic techniques due to multiple advantages, such as the high level of accuracy achieved by applying these techniques, their efficiency, the availability of products such as 3D models to be consulted everywhere and at any time, etc. In this sense, several studies have used 3D models to analyse the geometric aspects of Egyptian tombs based on basic primitives (Mozas-Calvache et al., 2023). In this context, Historic Building Information Modelling (HBIM) (Murphy et al., 2009) supposes an interesting information system to support this type of geometric studies among other purposes (documentation, virtual reconstruction, structural analysis, etc.). Depending on the Level of Geometry (LOG) and Grade of Accuracy (LOA) (Brumana et al., 2018; Banfi et al., 2019) of the implemented scan-to-HBIM application, the analysis of the geometrical aspects of any historic building can achieve a high level of detail and accuracy.

1.1 Qubbet el-Hawa: The QH31 funerary structure

The necropolis of Qubbet el-Hawa (Aswan, Egypt) (Figure 1a) is located on the west bank of the Nile River. The necropolis is composed of more than 100 hypogea (Edel, 2008) excavated on a hill during several periods of ancient Egyptian history. The large funerary structures located in this necropolis impress any visitor by their magnificence despite the fact that these tombs were constructed almost 4000 years ago. This is the case of QH31, where the public space excavated inside the hill is more than 30 metres long. Within these spaces, dedicated to the offering to the deceased (governor Sarenput II, XIIth Dynasty), the hypostyle hall is a prominent area. It is composed of a rectangular space of about 12.1 metres long, 8.6 metres wide and 4.9 metres high (about 23, 16.4 and 9.3 royal cubits respectively). In this space are distributed six pillars grouped in two rows located next to a central longitudinal nave. The hypostyle hall is delimited by vertical walls polished in great detail (Figure 1b). The selection of this structure to analyse several geometric variables such as inclination, parallelism and perpendicularity, was related to the apparent great accuracy achieved by ancient constructors in this space. In this sense, this analysis could help us to contrast several hypotheses about the constructive processes of this type of structures.

Figure 1. Necropolis of Qubbet el-Hawa: a) situation of the QH31 tomb; b) view of the hypostyle hall.

1.2 Objectives

The main objective of this study is the development of a methodology for obtaining basic primitives to analyse the geometric behaviour of Egyptian funerary structures and more specifically of the hypostyle hall of the QH31 tomb. This information will be used to contrast several established hypotheses about the constructive processes carried out by the ancient Egyptians, considering the planning, stakeout, measuring and excavation tools, etc.

2. METHODOLOGY AND APPLICATION

The methodology followed in this study supposes an extension of that developed by Mozas-Calvache et al. (2023) to analyse the geometry of several tombs in Qubbet el-Hawa. The previously developed study analysed general geometric aspects, such as dimensions, proportions, orientations, etc., of the main spaces of several structures (e.g. halls, corridors and vertical shafts). In this case, the goal was related to other geometric information of specific elements (walls and pillars) due to their importance in the hypostyle halls of these funerary structures. More specifically, we analyse several aspects such as inclination, parallelism and perpendicularity of walls and pillars of the hypostyle hall of the QH31 tomb. In this case, the requirements for data density and accuracy were higher than in the previous study. To achieve this goal, we have developed a procedure based on data extracted from a 3D model obtained using TLS and close range photogrammetry (CRP). The workflow applied is shown in Figure 2. The first part describes the procedure followed to capture and process data and is divided into three techniques: TLS, surveying and CRP. The second part includes the geomatic results obtained after implementing these techniques, which were mainly based on a 3D model and the extraction of several sets of points that define the geometry of each element. Finally, the analysis of those geometrical aspects to be studied based on the normal vector that describes each geometry. Therefore, we used both TLS and CRP techniques to obtain a product with a high density of points, geometrically contrasted and containing real texture, and considering the need to improve the efficiency of field work with respect to traditional studies due to the presence of workers and tourists during the acquisition works.

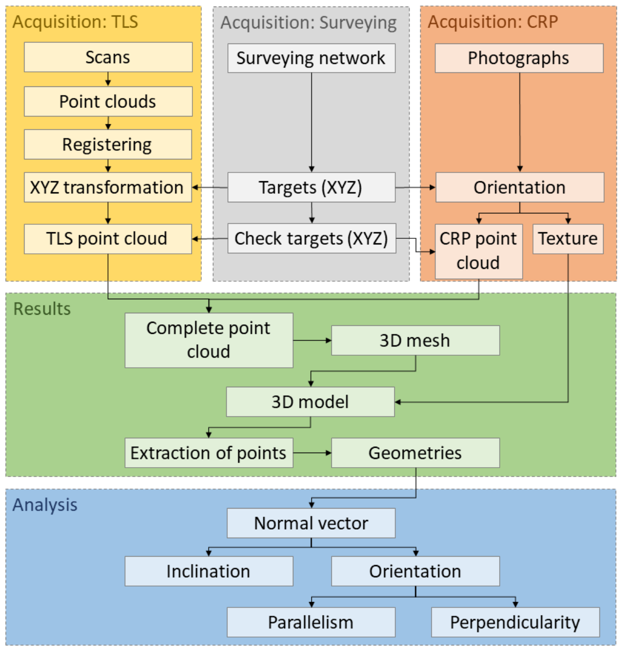

Figure 2. Methodology developed in this study.

Obviously, the acquisition work considered the geometry of the hypostyle hall and, in particular, the presence of the six pillars that caused some occlusions. The existence of this complex scene made it necessary to carry out a previous data acquisition planning stage. Other aspects such as illumination conditions were also considered previously to the development of the acquisition works.

The TLS acquisition consisted of twelve scanning stations distributed at each intersection of the longitudinal naves with the transverse spaces (Figure 3). This acquisition was carried out using a Faro Focus X130 scanner without considering image capture because the 3D model texture was subsequently obtained using photogrammetry. Considering the distances from scanning stations to the object of various metres (Figure 3), the large overlaps between adjacent stations and the requirement for high acquisition efficiency, we selected a point resolution of about 12 millimetres at ten meters, which implies about 3 minutes of scan duration. The orientation of the twelve point clouds (TLS) included their relative registering process. This procedure was developed using Faro Scene software. We obtained overlap values higher than 32% and an average error of about 0.8 millimetres thanks to the distribution of the scanning stations developed to survey this scene. After that, an XYZ transformation was applied to the complete point cloud to reference this product in the Coordinate Reference System (CRS) of the project. We used several well-defined targets identified in the point cloud to perform this transformation. In this sense, the determination of each control point was calculated using an average point obtained from the selection of a large set of points that defined each target. The coordinates of the targets referred to the CRS of the project were obtained using a total station from points of the surveying network. In addition we also used other checkpoints to contrast the point cloud, obtaining average error values of about 3 millimetres.

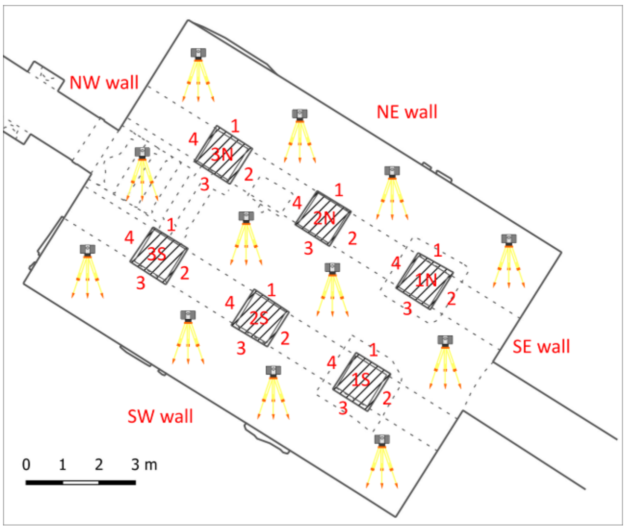

Figure 3. Location of TLS stations and coding scheme of walls and pillars.

The acquisition of photographs (CRP) was performed using a conventional camera (Sony Alpha 5000) with a wide-angle lens (16 mm focal length). We considered the recommendations of the CIPA Heritage Documentation for architectural photogrammetric projects using non-metric cameras (called 3x3 rules) (Waldhäusl et al., 2013). More specifically, we captured normal and convergent photographs covering all of the scene from different viewpoints. The camera was remotely-controlled using a mast of about 2 metres to lift the camera over high zones. The illumination was based on several lights attached to the camera mounting system that facilitated shadow avoidance (Figure 4). The orientation of photographs was carried out using several well-distributed targets located on the walls and pillars. The coordinates of the targets were obtained using a total station from several points of the surveying network of the project (referred to the CRS of the project). Additional targets were used as checkpoints to contrast the results obtained after processing. We obtained accuracies of about 5 millimetres in this assessment. The CRP processing was developed using Agisoft Metashape software and the results were a point cloud and the texture to be included in the final 3D model.

Figure 4. Acquisition of photographs using an annexed illumination system.

After the processing stage we obtained two point clouds, one from the TLS and another from the CRP. The next stage consisted of obtaining a common 3D model (Figure 5) using the geometry from the TLS and the texture from the photogrammetry. It should be noted that the geometry was also complemented with additional points extracted from the CRP data in zones where the TLS data presented gaps. These data gaps were caused by occlusions (e.g. pillars) and scene complexity (e.g. the presence of fissures in the walls that were not completely visible from scanning stations). In this application, the 3D model geometry was mostly based on TLS data, with only some reduced areas obtained from CRP. We have to note that the final point cloud was filtered using a distance threshold of one centimetre to reduce data volume and obtain a product with a regular point density. This filtering technique is available in several software applications, although depending on the purpose of this procedure we can also use other filtering algorithms, such as those summarized by Han et al., 2017.

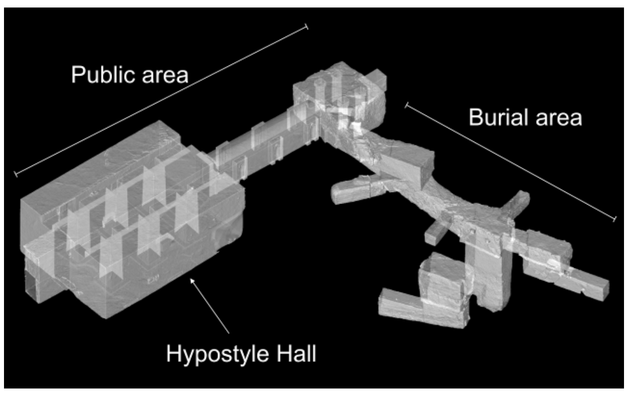

Figure 5. 3D model of QH31 including the hypostyle hall.

From the 3D model we extracted 28 point clouds related to each element to be analysed (walls and sides of pillars). The identification of the points that determine each geometry was carried out visually. At this stage, the texture of the model assisted us in identifying the points related to each element. Once these points were extracted, a basic geometry (plane) was fitted to each set of points (Figure 6a). This procedure can be performed using several algorithms based on least square fitting, principal component analysis, singular value decomposition, etc. (Huang and Tseng, 2008; Valero et al., 2012). In this study, we used Maptek Point Studio software to obtained fitted planes without any restrictions (e.g. vertical planes) and using the complete set of previously extracted points. We obtained deviations of less than one centimetre in all cases. As an example, Figure 6b shows the deviations obtained on two sides of the 1N pillar (sides 1 and 2 in Figure 3).

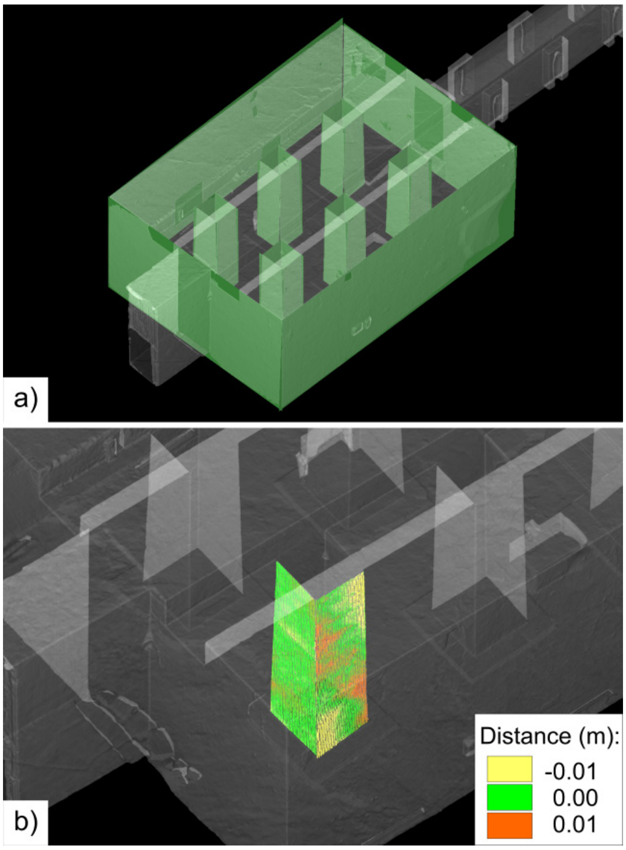

Figure 6. Geometries obtained from point clouds: a) planes determining walls and pillars; b) example of deviations of the extracted point clouds with respect to the fitted geometry.

The results of the distances of the point clouds with respect to the fitted geometries gave us a quantitative value about the flatness of these elements. This aspect is very interesting from a constructive point of view because it is usual that ancient Egyptian builders tried to develop walls and pillars as flat and polished as possible.

In addition to the analysis of flatness, the fitted geometries were also used to determine some aspects of the geometry such as inclination, parallelism and perpendicularity. In these cases we used the normal vector, which defines each fitted geometry, to obtain the inclination and orientation of the elements. The inclination was considered with respect to the vertical, while the orientation was based on the azimuth that defined the alignment of the geometry. The study of parallelism and perpendicularity was based on the comparison of the orientations of two specific elements.

3. RESULTS AND DISCUSSION

The results obtained after applying the proposed method to the QH31 funerary structure were based on the 3D model determined from both point clouds (TLS and CRP). In this sense, we obtained a dense 3D model where each geometry (plane) was fitted to a previously-selected set of points. Therefore, we obtained 4 planes defining the geometry of the walls and 24 planes for the pillars. Considering these planes, we analyse their inclination, parallelism and perpendicularity based on the 28 normal vectors that defined these geometries.

Firstly, the inclination values are related to the deviation with respect to the vertical considering the z-component of each normal vector. The results show an average value of inclination (Figure 7) of the four walls of 0.2 degrees (standard deviation of 0.23 degrees). Considering the six pillars, the average inclination is one degree (standard deviation of 0.27 degrees). Thus, all pillars show similar average values (from 1.2 to 0.8 degrees) (Figure 7). Evidently, the pillars were constructed with a certain inclination trying to give a greater sense of stylization to the hall. From a constructive point of view, the capacity of ancient constructors to develop vertical and inclined planes with a certain grade of inclination should be emphasized considering our results. They used the plumb bob, the square level and the plumb rule to determine verticality (Harrell, 2008) with great accuracy, as our results demonstrate.

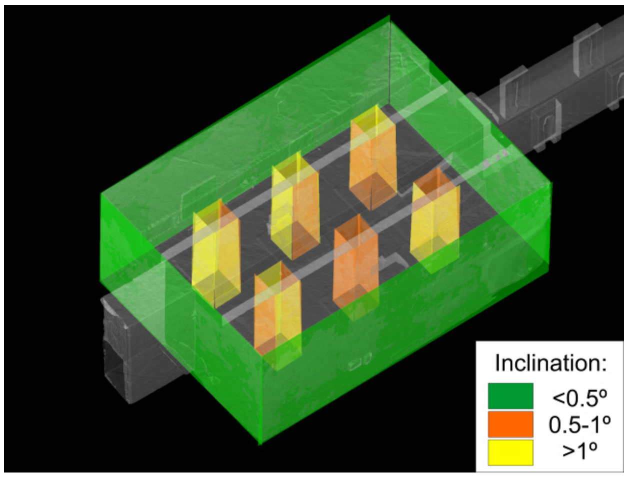

Figure 7. Inclinations of fitted geometries.

On the other hand the orientation of the planes, based on the XY components of the normal vectors, was used to analyse the parallelism and perpendicularity between them by comparing the angles obtained. The results obtained for the walls and pillars are shown in Figure 8 considering the coding shown in Figure 3 related to the situation of each element.

Firstly, we analysed the four walls. In the case of parallelism (Figure 8a), the walls show incredible values of 0.12 and 0.06 degrees of deviation considering the long and short walls respectively. Next, the perpendicularity between each wall and the two adjacent walls was analysed (Figure 8b). This calculation gave us four perpendicularity values. The results show an average deviation value with respect to the right angle of 0.08 degrees, with a maximum value of deviation of 0.15 degrees. Considering these results, we can assure that the construction of the walls followed an accurate procedure to guarantee the almost angular perfection of this hall. In this sense, we must consider that the parallelism between two alignments is easier to achieve by maintaining a certain length along them, for example, using measuring cords (Harrell, 2008). However, the achievement of perpendicular planes involves the use of a more advanced stakeout and construction procedure, probably based on triangle calculations and the use of tools such as the builder's square (Harrell, 2008), used in ancient Egypt to stake out squared edges and corners.

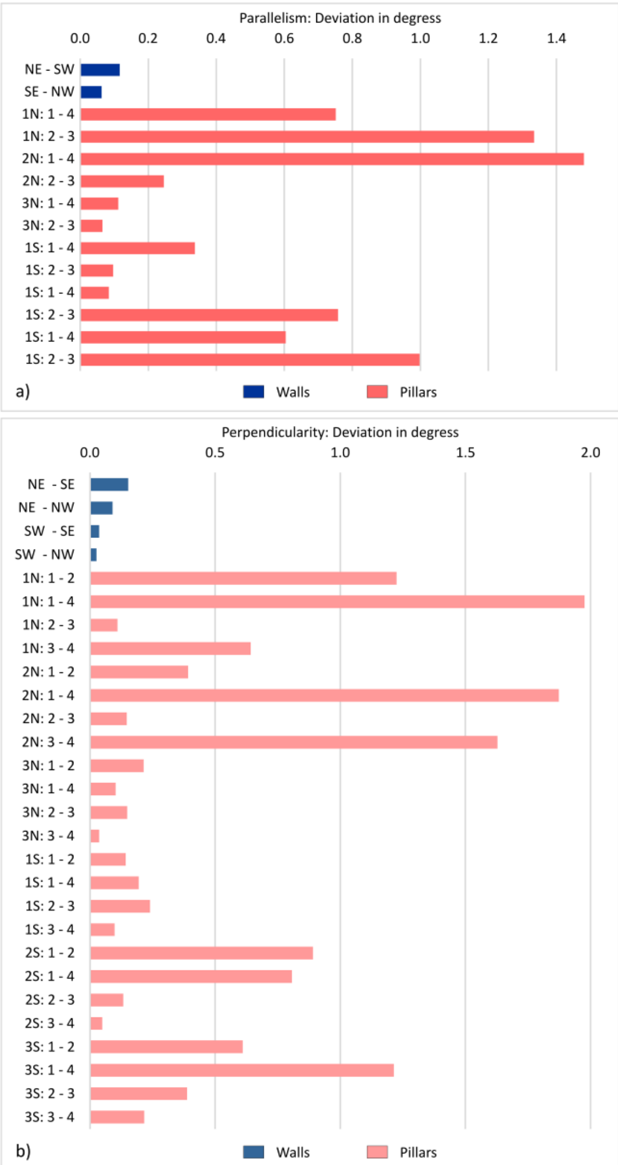

Figure 8. Results of: a) parallelism and b) perpendicularity.

In the case of the pillars, the analysis of the parallelism is carried out between opposite planes of each pillar obtaining twelve values in total (Figure 8a). In this case, the average deviation of the angles was 0.57 degrees with a maximum value of about 1.5 degrees. As shown in Figure 8a, only 3 cases out of 12 show deviation values greater than one degree. In the case of perpendicularity (Figure 8b), we calculated the angles from each plane to the two adjacent ones, obtaining 24 values. The average deviation was 0.56 degrees, although there are some values of almost 2 degrees. In this sense, only 5 cases presented deviations greater than one degree. To summarize, the results of parallelism and perpendicularity of the pillars have shown worse values than those detected in walls, although they achieved a great geometric consistency with the rest of the hall. In this sense, deviations of about one degree in elements that have a length of about one meter are not easily detectable. In addition, the existence of an inclination in these elements conditioned the deviation of some sides in contrast to the almost perfect values detected in vertical walls.

Additionally to the study of each element independently, we also included the analysis of the alignment of the pillars jointly considering their distribution in two rows (N and S) and three distance levels from the entrance (1-3). To develop this analysis, we fitted 4 planes that included sides 1 and 3 (Figure 9a) and 6 planes from sides 2 and 4 (Figure 9b) considering all of the pillars. The distances obtained from the point sets extracted with respect to the fitted geometries are displayed in Figure 9. The results show standard deviations of these distances between 0.003 and 0.011 metres, indicating a great level of alignment of the corresponding sides of the pillars in each case.

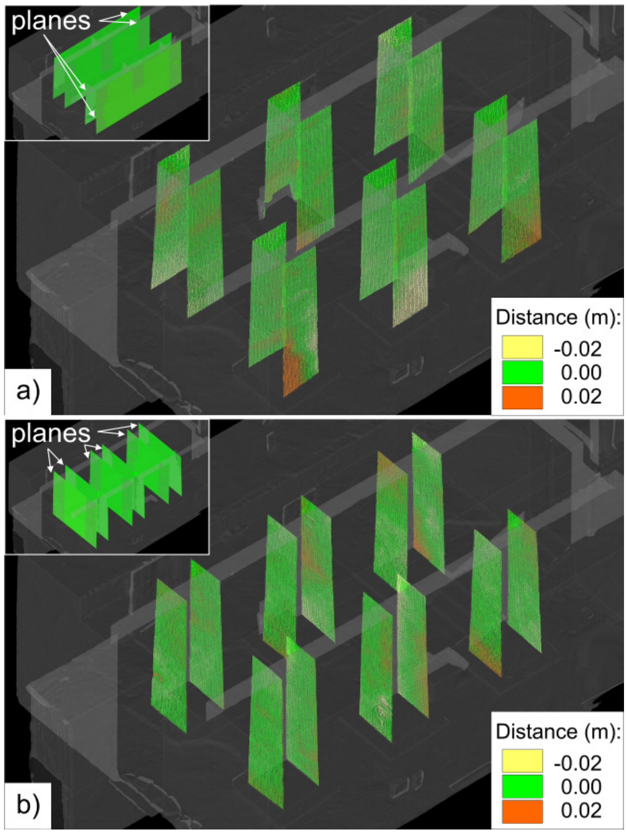

Figure 9. Results of: a) parallelism and b) perpendicularity.

Finally, the analysis of the angular deviations of the sides of the pillars with respect to the walls shows average errors of 0.02 degrees and standard deviation values of 0.55 and 0.58 degrees for parallelism and perpendicularity respectively. The maximum deviation value of 1.5 degrees is shown on 3 sides. These results confirm the great alignment of the pillars with respect to the walls, although there are some sides that show worse behaviours.

The hypothesis about the construction of this funerary structure described by Martinez-Hermoso et al. (2015) and based on Arnold (1991) is consistent with the results obtained in this study. Following this hypothesis, the excavation works began with a preliminary narrow tunnel that defined the axis of the tomb. This tunnel was located at the ceiling level of the hall.

From this tunnel, each space was dig to the sides and in depth until the previously planned dimensions were reached. The pillars were initially connected to the lateral walls until, at a later stage, they were retreated backwards leaving these elements independent of the walls. This aspect could condition the worse geometric definition of the pillars in contrast to the almost perfect behaviour of the walls, such as is demonstrated by our results. In any case, the capacity of the ancient Egyptian to stake out and execute the construction of this structure with a great accuracy is clearly demonstrated.

4. CONCLUSIONS

The methodology proposed in this study has demonstrated its feasibility for determining some geometric aspects of funerary structures by analysing those fitted planes obtained from a set of points, which were extracted from the 3D model of the tomb. The determination of these geometries has allowed us to obtain a direct evaluation of the flatness of the elements, while the remaining aspects analysed are easily obtained from the components of the normal vector that defined each plane. The use of two geomatic techniques to obtain a combined 3D model has revealed its efficiency, considering field acquisition, guaranteeing the complete coverage of the scene and obtaining an accurate and real-textured model.

HBIM systems can provide a powerful tool for performing this type of geometric studies by means of parametric modelling based on scan-to-HBIM data. However, we suggest the use of this possibility when its development is justified considering other purposes, such as documentation based on parametric simplified models, virtual reconstruction, structural analysis, etc. In cases where only a basic geometric analysis is demanded, we recommend the methodology proposed in this study based on normal vectors (obtained from geometries fitted to points extracted from 3D models). In this sense, the "scan-to-geometry" methodology described here offers an effective tool for obtaining rapid analyses of the geometry in order to study the constructive processes carried out in this type of structure.

Considering the results obtained in this study, we can indicate several conclusions about the constructive aspects analysed in the hypostyle hall of the QH31 funerary structure. Firstly, the level of flatness of all elements is remarkable, as shown by the deviations detected between the extracted points with respect to the fitted geometries. Secondly, the plan of this hall is almost perfectly rectangular, with almost vertical walls and showing a great level of parallelism and perpendicularity. The constructive techniques used by the builders clearly had to include accurate measurements and precise guiding systems. Thirdly, in the case of pillars, the excavation of these elements was also accurate although Egyptian constructors did not reach the same level as in the case of the walls. In this sense, we must consider that the construction of these elements was evidently more complex due to the fact that they have a certain inclination of about 1 degree. These results are also coherent with the constructive procedure used in these structures, where the pillars are defined in the last stages of excavation and obviously when the accumulation of errors is greater.

Future work will focus on improving field acquisition efficiency with the use of MMS and the assessment of the accuracy obtained by applying these systems in contrast to the geomatic techniques used in this study. In addition, we will extend this study to other funerary structures, including other areas of the tombs that could be fitted using other basic geometries such as cylinders, cones, etc.

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