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Digital Documentation in Narrow Burial Spaces Using a 360° Borescope Prototype

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Abstract: This paper illustrates and discusses a novel method for the digital documentation of human remains in narrow spaces. A 360° borescope prototype made up of a panoramic camera and a lighting LED system was designed and assembled to acquire data in confined spaces for photogrammetric processing. A series of laboratory experiments were planned to assess the method's validity. A modern concrete tunnel and a mock grave were surveyed using surveying instruments and a laser scanner, comparing the results with the borescope prototype. Then, data acquisition was moved to the field, i.e., in a real case study. Two burial vaults in a church containing human remains were selected and surveyed. The remains were accessible only from small breaches. The results show that using the 360° borescope is suitable for documenting narrow/confined spaces with minimum alteration of the scene. This result can be of interest for archaeological and forensic purposes, especially when the context is hardly accessible, with minimal intervention on the scene.

Keywords: 360° cameras; borescope prototype; digital photogrammetry; human remains; narrow spaces; osteoarchaeology

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1. Introduction

1.1. State of the Art

The manuscript presents a novel method for digital documentation based on photogrammetry using a 360° borescope prototype, which was developed and tested to capture human remains in narrow spaces, such as burial vaults. The application is particularly relevant in those cases where exposed human remains need to be recorded before any possible intervention in the original context, such as an archaeological excavation or forensic documentation. The complexity of the spaces often prevents the use of more traditional solutions for digital recording, such as laser scanning or photogrammetric techniques.

The need to obtain a correct and complete record of human remains is usually shared by the domains of Archaeology, Biological Anthropology, or Forensic Sciences, including Osteoarchaeology and Forensic Archaeology as interdisciplinary fields between the aforementioned disciplines. After the impressive development of digital 3D recording techniques in recent years, the digital recording of human remains significantly increased. Digital photogrammetry has been widely used to record human remains for forensic [1–4] and archaeological [5–7] applications.

The work of Luis et al. [5] is essential for the scope of this work as it shows a similar target and field of application: the digital recording of human remains in inaccessible contexts. The advantages of this approach are clear: traditional documentation carried out using analog/digital photography can be used for general or detailed documentation purposes but not to document the morphology/geometry or to obtain metric outputs.

Traditional documentation can be achieved with direct surveys and human remains' drawings, often delivering excellent results. Nevertheless, the main limitation is the time required for the operations, which are usually carried out by high-skilled personnel with knowledge in human and non-human osteology and taphonomic processes, and a relevant ability in drawing [8,9].

Most applications of digital recording of human remains can be divided into two categories:

- On the field, where human remains are recorded on-site within their context, which is usually a funerary context for Archaeology, while forensic cases are usually out of funerary contexts;
- Laboratory applications, including recording bone morphology for biological and pathological profiling.

An intermediate case is the 'block excavation', i.e., the removal of complex archaeological burials from the field and the surface they are on to be examined later in the lab. Although it is always preferable to record the human remains in their original context, documentation can also be carried out after the burial removal.

The aims of these applications are different. On-field documentation is mainly aimed at recording the surrounding context of the burial, the positioning of the buried individual and skeletal districts, the visible consequences of taphonomic effects, and the relation with possible grave goods or other findings. Lab documentation is mainly aimed at recording the morphology of single bones (or biological tissues in case of mummies) and every detail that can bring information about the conditions of life, and the reasons for the death of the individual (pathological marks, post-depositional marks, perimortem marks).

The differences between these approaches are evident: documenting the details of single bones on the field is complex, considering that only one side is visible because the other lies on the ground. In most cases, bones must be cleaned from the soil with dry or wet systems to assess them and correctly capture the details. Moreover, except for the aforementioned cases where the examination is performed in a laboratory, in most applications, human remains are moved from the field and stored in cases, losing every connection among them and with the context.

This paper will explore a novel 360° borescope prototype, working on-site with minimal intervention on the scene. The use of 360° cameras for photogrammetric purposes was established a few years ago, and their use is constantly increasing. Furthermore, 360° commercial cameras usually have two or more sensors and two fisheye lenses to capture the area. A popular way of acquiring photogrammetric data is to capture a video from which the frames are successively extracted.

Different papers considered the problems related to the digital recording of narrow and complex spaces using photogrammetry. Most approaches used fisheye lenses or spherical cameras to increase the field of view and reduce the number of images, guaranteeing sufficient overlap between consecutive images (for some examples and applications in different application, see [10–22]).

The proposed solution was explicitly developed to record spaces not normally accessible by humans. The camera must be inserted through a small aperture and moved using a telescopic pole or a tube. The maneuverability of the system is also very limited for the confined geometry, and the camera-object distance can be smaller than 0.1–0.2 m. At the same time, good lighting conditions must be achieved with an illumination system installed on top of the camera.

1.2. Main Typologies of Confined/Narrow Burial Spaces and Digital Recording

There are many typologies of graves, depending on the historical period and the human culture. For this study, we consider those cases where there is a space surrounding the human remains at the time of surveying. The most frequent case is the underground burial vault or the burial recess, or any other typology that includes some sides and a cover that closes and protects the human remains to create a volume around the body that separates it from the outside. This structure is considered in this study as a narrow space.

In this sense, a simple coffin or a 'cappuccina tomb' also could be considered, although they would be more complex cases to document. In ancient contexts usually discovered during archaeological excavations, the space around the body is often filled with sediment that filled up the empty space over the centuries. In this case, the human remains are partially or entirely covered by the sediment, and no documentation can be carried out before an excavation.

The digital documentation of human remains in narrow spaces can be helpful for several reasons. It records the burial context as it is, without modifications or with minimal intervention, without the complete removal of any cover. This removal can sometimes be carried out only with extensive work or the complete dismantling of the previous structure. For archaeological purposes, it could be a remote assessment that sometimes even avoids exposing human remains. In the case of forensic purposes, it could be a method with minimal modification of the context, increasing the reliability of legal evidence.

When human remains are positioned inside a structure, they usually are no longer visible. It is difficult to assess them without removing their cover, whether it is a stone slab or a brick archivolt, especially for graves not designed to be reopened because their cover is permanent. Graves designed to be periodically reopened can be easier to access but pose some surveying issues. Both digital photogrammetry and laser scanning usually need some space around the object to be recorded for the human operators and the instruments, to reach the necessary overlap between different frames for photogrammetry, and to move the instrument to avoid blind spots due to physical obstacles for laser scanning. Moreover, when dealing with underground burial vaults or burial recesses, the open part is usually positioned only on one side of the volume of the structure; this is an additional constraint for digital recording techniques, requiring the acquisition of data only from one direction.

Although the method presented here is designed to digitally record human remains with minimal intervention in the surrounding context, an opening is necessary to introduce the 360° prototype. In those cases where a removable slab is existent and can be lifted, no other actions are required; in other cases where no opening exists, a new one is necessary and needs to be carried out, limiting the material removal.

The overall requirements to apply the presented method are as follows:

- Human remains have to be located within a structure that isolates them and creates a space around them, such as a burial vault;
- The space around the human remains must be partially empty at the moment of the survey;
- An opening is necessary to insert the used gear; simultaneously, the empty space inside the structure must be large enough to move and direct the gear;

The paper is structured as follows. After introducing the proposed method for digital recording, some tests were performed in the lab to assess the pros and cons and evaluate the metric accuracy. Then, the procedure was used in a real case study: two underground burial vaults in the church of SS. Giacomo e Filippo in Chiesa in Valmalenco (Italy).

2. The Proposed Method: General Description

The proposed solution for the digital documentation of narrow spaces is based on a 360° camera mounted on a special frame, illuminating the entire scene around the camera with LEDs. The lighting system was designed to provide sufficient light in completely dark environments. It consists of multiple LED strips powered by a 12 V battery for use in areas without on-site electricity. It also features minimal power consumption and can be used for several hours before recharging the external battery.

An image of the prototype used in this paper is shown in Figure 1. LEDs are installed on both faces of the frame (i.e., oriented like the camera lenses). LEDs are also installed around the frame to illuminate the scene perpendicularly. The different strips are not part of the same circuit. They are selectively turned off depending on the characteristics of the space to be documented. The user can perform some trials before the real acquisition to find an optimal light configuration. The gear is installed on an extendable pole to reach places outside the range of regular camera sticks.

Figure 1. Details of the prototype for the 360° borescope and the on-site work with the system installed on a telescopic pole.

The camera used for creating the prototype is an Insta360 ONE R 360° camera, which can acquire 5k videos and images. This paper used only 5k (5120 × 2880 pixels) videos for the space's complex geometry, which requires a very short baseline between consecutive images. The camera is controlled using an application installed on portable devices (mobile phones and tablets) through a wireless connection, obtaining a real-time video preview. The different characteristics of the small and narrow spaces considered in the paper usually require specific setups. A preliminary on-site inspection is generally necessary to develop a strategy for image acquisition. The 360° gear is installed on the chosen pole and progressively inserted into the narrow space. Before acquiring the video, a scale bar is inserted into the space to provide an external reference for scaling the photogrammetric project. Indeed, projects carried out with images have an overall scale ambiguity that can be removed using a known distance. When the context cannot be modified, i.e., no reference objects can be introduced, projects without external metric information are still feasible, but the correct scale of the model cannot be set. We developed a set of scale bars with different lengths printed through laser on an anodized aluminum rod.

The video acquisition and processing workflow using the 360° borescope prototype is shown in Figure 2. After a preliminary visual inspection of the area to be captured, the LED and the camera must be connected to the pole, and the parameters for video acquisition can be tuned with a few trials. In the case of the LEDs, the user can decide which will be active, their power, and if some LEDs require an additional screen on top to obtain more diffused and soft lights. At the same time, the parameters of the 360° camera must be set to obtain a sufficiently sharp video with good illumination conditions and little flares. Choosing a tube (or pole) is also fundamental regarding flexibility, length, and weight. All of the operations are remotely controlled with the camera using a wireless connection so that a preview is available on a mobile phone or tablet.

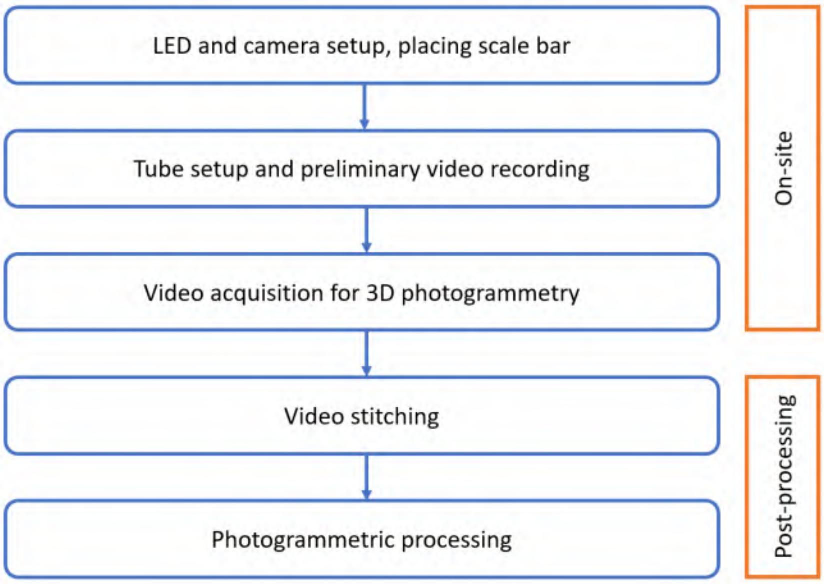

Figure 2. Overall acquisition and processing workflow with the 360° horoscope prototype.

One or more photogrammetric scale bars are then inserted into the space. They have a variable length from a few centimeters to 1.5 m, depending on the geometry of the area. The acquisition can also be carried out without using a known scale bar, but an overall scale ambiguity can affect the photogrammetric model. After finding a good initial setup, a first video is acquired inside the space. An operator handles the tube (in some cases, two operators, mainly when the area to be investigated features several meters). In contrast, another operator constantly observes the monitor and tries to identify the main challenges for recording the area. This preliminary video is also processed on-site so the team can develop a good strategy for the photogrammetric acquisition.

A set of single images can also be acquired instead of a video. They usually feature better quality compared to thr frames extracted from videos. Capturing some images also allows us to verify the camera's focus setting. Then, the videos for photogrammetric processing can be captured. Usually, the same acquisition is repeated twice to obtain redundant data.

The raw files are then downloaded and processed with the camera's proprietary software (Insta Studio) and exported into an MP4 format. Compared to a traditional borescope, the 360° solution captures all of the surfaces around the camera without privileging just a single direction. The video also becomes the first product of digital documentation in which the user can interactively rotate the point of view.

Acquisition parameters are set to combine the camera's movement (and inevitable vibrations) and visual quality. The experiments reported in the paper were carried out with exposure times shorter than 1/80–100 s and an ISO lower than 500. An example of a frame extracted from the video is shown in Figure 3, which is based on the equirectangular projection, also called the latitude-longitude projection.

Figure 3. Example of 360° image acquired with the proposed solution (top), and two frame images generated by changing the field of view of the equirectangular projection.

The frame (or the entire video) can also be opened with specific software, providing a more traditional "bubble" visualization in which the user can rotate the point of view and turn the image into a frame-based projection. Nevertheless, the light is not sufficiently strong to illuminate deep scenes (the background is quite dark), and the camera must be moved (if possible) to the end of the cavity.

Metric documentation is conducted with a photogrammetry project and the Agisoft Metashape software. The video is imported into the software, and a set of keyframes are extracted at a specific frequency. The equirectangular frames are then processed with a standard photogrammetric workflow (image orientation, dense point cloud generation, mesh production, texture mapping) to create a textured 3D model. The spherical camera model must be set at the beginning of processing.

Projects are usually conducted with several videos acquired in the same cavity, moving the camera not only along the longitudinal axis to try to cover the entire space. Several longitudinal strips shifted along the transversal direction are also recommended. The resulting photogrammetric projects can comprise several hundred (or thousand) images, requiring powerful computers for image processing. The processing time can take several hours.

3. Experiments in the Lab and Results

3.1. Lab Experiment N° 1: Accuracy Evaluation with Control Points

The first experiment in the laboratory consisted of a 2 m $\times$ 0.5 m $\times$ 0.5 m regular box made up of wood, which was built to simulate a possible underground grave.

A set of targets was stitched on three internal surfaces (before closing the box). They were also measured with a Leica TS30 total station, obtaining precise coordinates better than $\pm$0.002 m.

The 360° camera was placed inside the box with an extendible pole, capturing a 58-second video. The frames were extracted with a sampling rate of 2 frames/second, obtaining a total of 116 frames, which were processed in Metashape after setting the spherical camera model (Figure 4).

Figure 4. The rectangular box used in the first test (**top** row) and the visual results of the photogrammetric processing (**bottom** row).

The camera was inserted from a 0.1 m × 0.1 m hole, simulating the case of a small opening required during a real inspection. The box was completely dark inside (except for the low external light from the aperture). Thus, the only lighting source was the LED system installed on the camera.

Data processing was conducted using the standard processing workflow of Metashape, adding the ground control points in the images with manual measurements and importing the corresponding 3D coordinates measured with the total station.

The photogrammetric project was then registered in the total station reference system using a 7-parameter transformation (rotation, translation, scale) with different control point and check point configurations. Table 1 shows the results varying the balance between the control and check points. If all points were used as control points, the RMSE was below 0.02 m, corresponding to a relative error of about 1% compared to the overall size of the box.

Table 1. Comparison between reference coordinates obtained with a total station and the results with the proposed photogrammetric approach.

GCP and Check	RMSE X (m)	RMSE Y (m)	RMSE Z (m)
18 control points	0.014	0.017	0.011
no check points	-	-	-
6 control points	0.007	0.0019	0.007
12 check points	0.017	0.018	0.015
4 control points	0.008	0.008	0.001
14 check points	0.028	0.018	0.074

The experiment was then repeated with fewer control points placed at the box's beginning and end. The error magnitude was still comparable to the previous case because such a distribution is homogeneous and covers the entire object. The last experiment (4 control points and 14 check points) showed a significant error along the longitudinal axis of the box (Z). The chosen control points were placed close to the entrance and did not allow good registration results for their unbalanced distribution.

This is an important consideration. Indeed, the survey of the narrow geometries proposed in this paper did not allow one to use homogeneously distributed control points. The overall registration in an external reference system is problematic. It could result in inaccurate metric results when the user wants to determine measurements using the proposed method and data acquired outside with other methods. An example could be estimating the thickness of the vaulted surfaces of tombs.

3.2. Lab Experiment N° 2: Surveying a Tunnel with a Reference Geometry from Laser Scans

A modern underground concrete tunnel was selected to simulate the narrow environment in the second test. The tunnel was about 1.20 × 0.9 m, and only a portion was surveyed (close to the entrance), i.e., about 4 m long. The small tunnel, painted with a dark blue color, makes photogrammetric processing more complicated for the additional problem of detecting a set of tie points with a good distribution in the images.

Laser Scanning and Photogrammetric Data Processing

The aim of this experiment was to compare the point cloud captured using 360° videos and a point cloud collected with a Faro Focus S70 laser scanner, which was as the reference for the comparison. The laser was placed on a small cart, capturing four scans inside the tunnel, which were registered using the ICP method, obtaining a registration precision better than ±2 mm. Five checkboard targets were also placed on three surfaces (the entrance and the lateral walls) to obtain a set of control points for the photogrammetric projects, as shown in Figure 5.

Figure 5. The laser scanning acquisition of the tunnel used in the second lab experiments.

Data acquisition using the photogrammetric solution based on 360° images was carried out with two different light configurations: (i) LED distributed on an external ring around the 360° camera, and (ii) the same configuration with additional front- and rear-facing lights.

In the case of LED distributed only around the camera, light is not directly pointing along the direction of the camera lenses. The video becomes slightly darker, especially along the direction parallel to the camera's optical axis. The video obtained using the second configuration is brighter, but we found a stronger flare caused by the front- and rear-facing LEDs. It is essential to mention that such an effect depends on the relative position between the camera and the LEDs. It remains relatively constant in the resulting frames, except when the camera-object distance changes significantly. Regarding photogrammetric processing, such a flare can be masked since its position in the frame is predictable using the same mask for the whole video.

Another fundamental parameter is exposure time, which must guarantee sharp frames when the camera is manually inserted into a narrow space. At the same time, the resulting video must be sufficiently bright to distinguish the elements and run photogrammetric data processing. After some tests, it was decided to use an exposure time of 1/80 seconds, trying to capture the cavity with slow movements, avoiding sudden movements or vibrations as much as possible.

The camera was inserted into the tunnel horizontally, i.e., the two lenses were directed toward the floor and the ceiling of the tunnel. This configuration was selected to simulate the presence of human remains laid on horizontal surfaces, as they would be better visible in the video if one of the two lenses captured the floor directly. The other option not tested in this experiment was inserting the camera so that the two lenses were oriented toward the lateral walls. Another difference between the two videos relates to the camera's trajectory in the tunnel. One video was captured by inserting the camera from the entrance to the end; the second one was captured by returning the camera. We discovered that the same user tends to produce smoother movement when the camera is retrieved instead of pushed.

The length of the video is also different, resulting in a different number of frames using the same sampling rate.

3.3. Accuracy Evaluation for the Tunnel

Data processing was carried out with Metashape after extracting the frame at a sampling rate of 1 Hz, obtaining two photogrammetric projects with 74 and 116 frames. The variable number of frames confirms the difference in acquiring videos by inserting the camera in the tunnel and returning it to the entrance.

After setting the spherical camera model, images can be oriented and a dense point cloud can be extracted. The last phases of processing are the extraction of a mesh and the production of orthophotos for the different surfaces of the tunnel. The five control points were then imported into the photogrammetric projects. After measuring the corresponding image coordinates (manual operation), the photogrammetric results were registered in the laser scanning reference frame with a 7-parameter transformation (scale, rotation, translation). This tunnel section was selected to determine the metric accuracy of the resulting point cloud. The experiment was carried out by physically entering the tunnel with the laser scanner and placing some control points.

After generating two dense point clouds for the two different photogrammetric projects, the comparison was carried out with CloudCompare software, estimating the discrepancy with a comparison extended to the four walls of the tunnel. Both photogrammetric projects provided very similar results, with an overall discrepancy of 0.008 m ± 0.006 m, as shown in Figure 6.

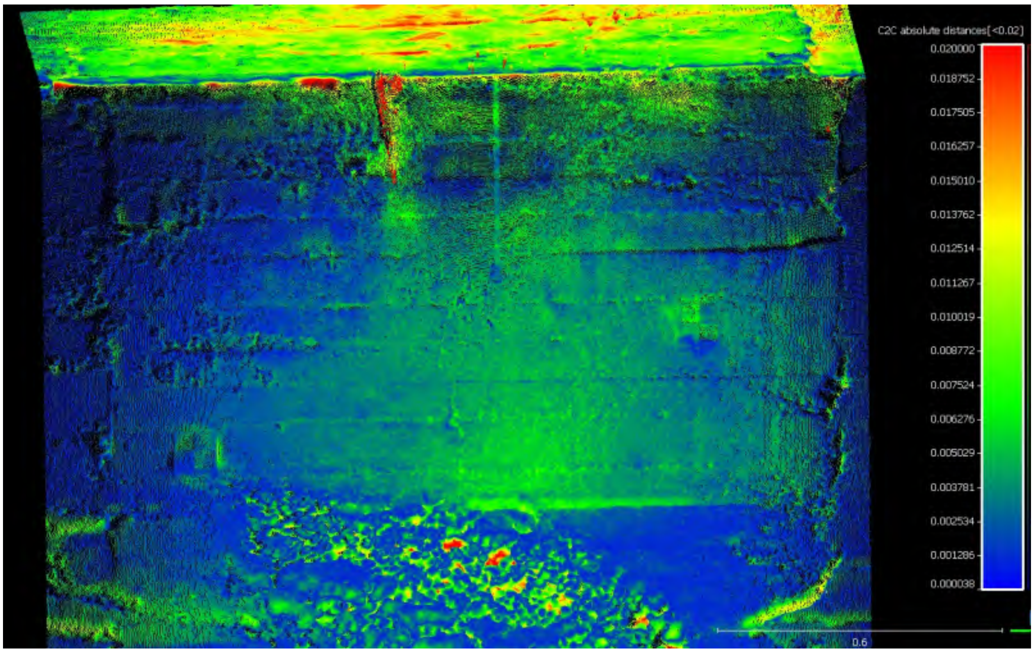

Figure 6. The laser scanning acquisition of the tunnel used in the first lab experiments. The scale bar is in meters.

It is interesting to understand where systematic errors are mainly located. A visual inspection of a transversal cross-section of the point clouds shows that the floor has a centimeter-level constant error (Figure 7, right). A possible explanation of this effect could be the short camera-object distance. When the camera was inserted and moved inside the tunnel, it was kept close to the floor, whereas the lateral walls and the ceiling were at a greater distance. We also noticed that the result achieved with the photogrammetric solution is smoother than the laser scanning point cloud. This is particularly visible in the top corners of the tunnel, i.e., at the intersections between the lateral walls and the ceilings (Figure 7, left).

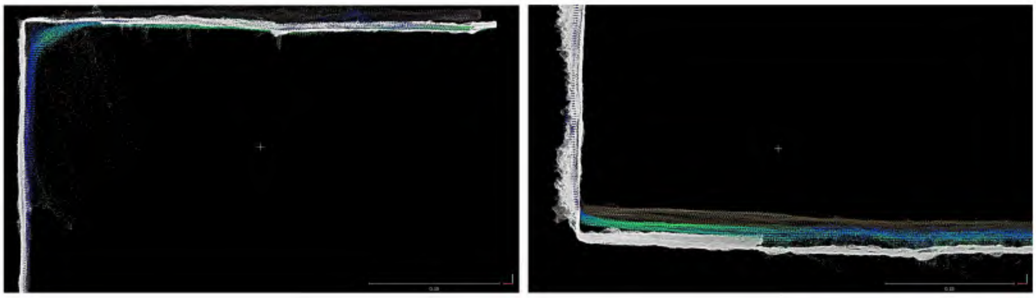

Figure 7. The laser scanning acquisition of the tunnel used in the first lab experiments.

Overall, a precision of about ±0.01 m can be achieved with the proposed method. After generating the final ortho mosaic, some image enhancement methods (such as a basic equalization of the histogram) can improve the image's visual quality, which remains darker compared to other more traditional photogrammetric applications. The different frames extracted from the video can also be individually enhanced before starting photogrammetric processing. However, this would result in an independent frame processing with slightly different parameters depending on the external geometry. For this reason, we preferred to work with the original frames and performed enhancement procedures only on the final outputs.

4. On-Site Recording and Results: The Church of SS. Giacomo E Filippo in Chiesa in Valmalenco (Italy)

4.1. Data Acquisition and Processing

The church of SS. Giacomo e Filippo is the old parish church of Chiesa in Valmalenco (Italy). The first church was built during the Middle Ages (11th century). The building was partially destroyed by a landslide in 1579 and demolished in 1644 when a new structure was built. Archaeological excavations were carried out in 2019–2020 inside the nave, revealing the remains of the old church and several burial contexts belonging to different periods (Figure 8, left). An example of the space to be documented is shown in Figure 8 on the right. As can be seen, a photo acquired from the breach does not provide a good view of the space, and its real inner size is not clear.

Two burial vaults located close to the facade and the perimeter walls were selected as case studies for this paper. Both burial vaults had their stone slabs still in place.

Figure 8. Inner view of the church with the excavated area.

The first burial vault (Figure 9) probably had a rectangular shape and two breaches, the first on one end and the other on the side. The breach on the end of the first burial vault was approximately 1 m × 0.15 m (width × height), and the second breach was roughly 0.3 m × 0.20 m.

Figure 9. The first burial vault with a detail of the two breaches.

The borescope prototype was manually introduced inside the first burial chamber passing through the two breaches. A first acquisition was performed from the breach at one of its ends: from this position and thanks to the telescopic pole, the borescope prototype could reach almost the entire inner space. A second acquisition was also performed from the other breach located on the side: this one could not reach all of the space, but it was helpful to integrate the first acquisition and acquire more data in the central portion of the burial vault.

Videos were acquired with a resolution of 5760 × 2880 pixels, a frame rate of 30 fps, ISO 500, and an exposure time of 1/100 s. The exposure time was reduced, taking into consideration the results of the lab tests because the small dimension of the only available breach made acquiring videos without vibrations more difficult. The rear-/front-facing LED lights were attenuated with a semi-transparent film to reduce the flare effect observed in the lab experiments.

An image with the textured mesh (about 1.8 million faces) with the camera locations is shown in Figure 10. The photogrammetric project was scaled by inserting a small scalebar. The space covers a surface of approximately 4.3 m × 1.9 m, and sections extracted from the mesh show an average thickness of about 0.45 m, which is not a constant value.

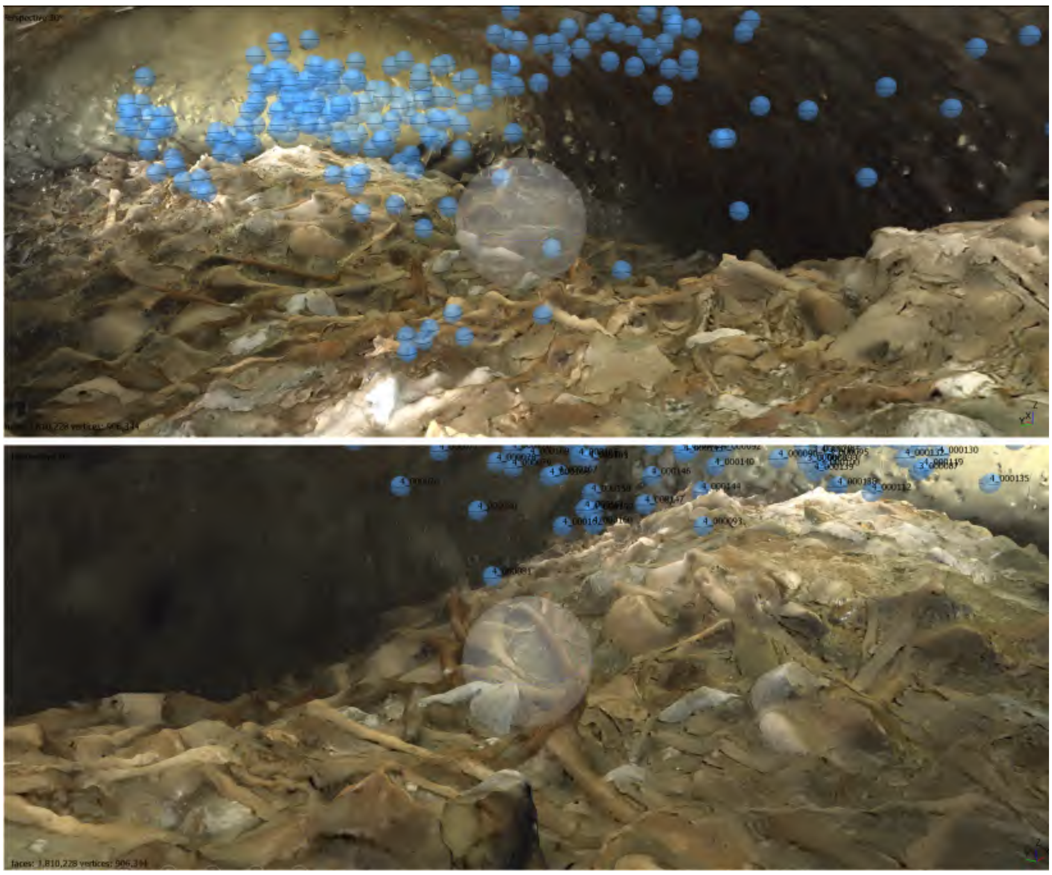

Figure 10. Textured mesh with camera locations (blue spheres) inside the first burial vault.

The final orthophoto is shown in Figure 11 and has a resolution (ground sampling distance) of 0.0006 m, i.e., sufficient to distinguish the different bones. The orthophoto was generated by projecting the bottom surface from outside, obtaining a reflected orthophoto. This allowed for the creation of a metric product with photorealistic content without manually deleting the triangles of the textured model. The final image could then be mirrored to obtain a representation oriented as a traditional orthophoto used in cartographic applications. The method would also allow for the production of orthoimages of the vaulted surface as visible from the inside.

Figure 11. The orthophoto of the first surveyed burial vault. The location of human remains is visible.

The second vault (Figure 12) had an uncertain shape and a single breach. The single breach in the second burial vault was roughly 0.1 m × 0.12 m. In this second case study, two different acquisitions with the same parameters were carried out inside the burial chamber: the first was aimed at acquiring the inner structure of the chamber and the human remains inside. In contrast, the second one sought to link the inner part of the chamber with the top exterior part visible inside the church's nave.

Figure 12. The second burial vault and its single breach.

A third acquisition was carried out in the church's nave to complete the survey of the top part of the buried chamber. For the first two videos, the developed light configuration was set with both LEDs distributed along the external ring and rear-/front-facing ones, as for the first burial vault. The third video was acquired with the light system deactivated. In addition, due to the small dimension of the breach and the presence of human remains, the camera's motion inside the chamber was limited and forced to follow only a specific path characterized by a descending and ascending branch (Figure 13).

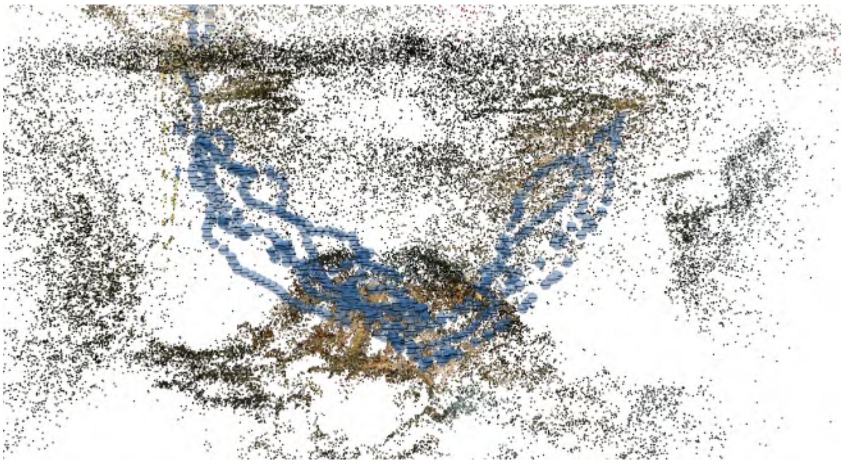

Figure 13. Acquisition path of the camera (blue spheres) inside the second buried chamber.

Data were processed using a procedure similar to the one discussed for the lab test. The main difference was that the frame rate sampling was set to 3 Hz for the second video to guarantee a sufficient overlap among frames while passing through the breach (total amount of images processed: 663). In this example, six points were set as control points outside the burial vaults. The control points were distributed approximately 5 m $\times$ 3 m meters apart on the church floor, and their accuracy was set to 0.01 m. A metric scale of 0.9 m was inserted into the vault as a check element to assess the metric accuracy of the reconstruction of the buried parts.

After running a bundle adjustment of the spherical image block average, the residual on GCPs was about 0.015 m while the residual on the reference scale bar inside the chamber was about 0.023 m. A comparison with a point cloud acquired with a laser scanner was carried out to verify any possible systematic error in the reconstruction of the church floor (Figure 14). The comparison showed an average discrepancy between photogrammetric and laser scanning point clouds of about 0.014 m , comparable with the residuals obtained on GCPs. The results did not show significant systematic errors in the reconstruction of the church floor. However, some boundary effects on a corner of the church characterized by poor lighting were still visible.

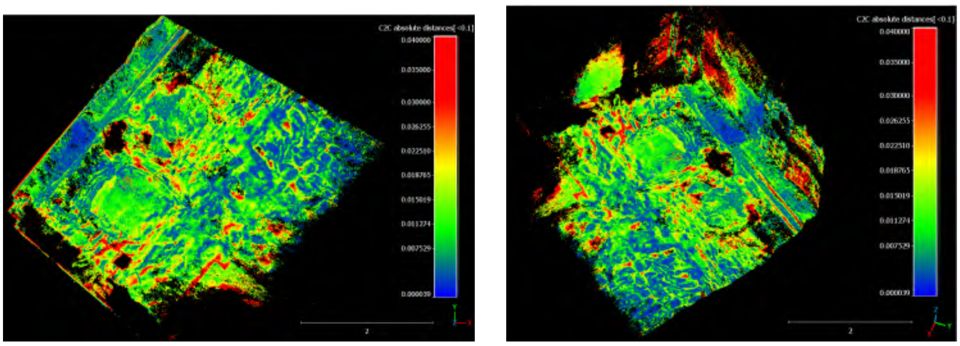

Figure 14. Comparison with laser scanning point cloud of the church floor for the second case study.

The final 3D model (Figure 15) showed a buried chamber with a squared shape (side of about 2.5 m) covered with a barrel vault composed of stone elements. The walls constituting the chamber presented an irregular shape. In the middle of the chamber, there was a pile of human bones in correspondence with a stone visible on the church floor and recognized as the chamber's slab.

Figure 15. Front view (**left**) and side view (**right**) of the reconstructed buried chamber of the second case study.

The reconstruction of the human bones is observable in Figure 16. In this second burial vault, the larger and smaller dimensions of the breach did not allow a uniform survey of the area, leading to some holes in the final reconstruction. In addition, the larger empty volume led to some poor lighting in the corners.

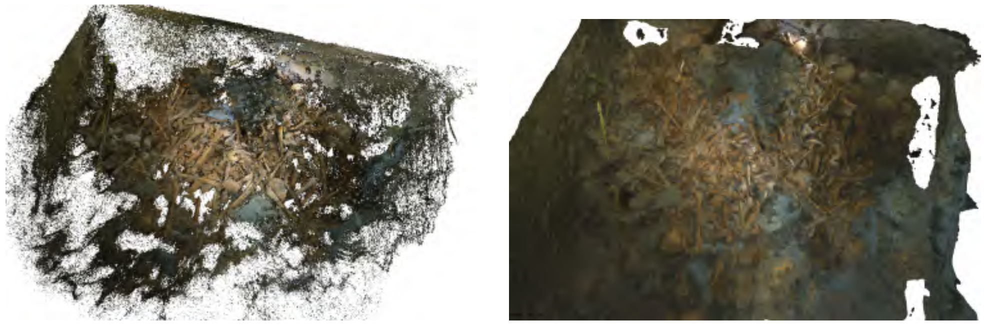

Figure 16. Results of human remains reconstruction for the second case study: point cloud (**left**) and resulting mesh (**right**).

4.2. Considerations and Discussion

Although the size of the first burial vault was measured with a certain degree of certainty from the outside (observing the morphology of the visible vault underneath the church's paving), the size of the second burial vault was unknown and not understandable from the outside. Its actual size was calculated only after photogrammetric data processing, which showed a much smaller squared room than the previous one.

The first burial chamber was recorded despite its size and narrow internal space. The less reconstructed parts were along the flanks of the vault, where the area was not enough to move the camera precisely. It is interesting to notice that, in this case, the light color of the bones helped to reflect the light of the borescope prototype, allowing the acquisition of brighter frames.

The quality of the results obtained from the documentation of the second burial vault was slightly worse than the first one. The main reason is that, although the inner space was smaller, the empty space between the vault and the first layer of bones was larger. This aspect, on the one hand, helped to move the camera inside the space in a more accessible way but, on the other hand, introduced some lighting issues: the greater distance between the lighting system of the camera and the surface resulted in darker frames and, consequently, in a less complete reconstruction of the objects.

These aspects suggest that the lighting system has a relevant impact on image acquisition: strong lights on the object could result in undesired flares or reflections coming from the object itself, resulting in overexposed parts of the images. Weak lighting conditions could result in darker frames showing fewer details for the photogrammetric reconstruction.

The obtained orthophotos were not flawless. The reconstruction of some details was not always optimal, especially those far from the path followed by the borescope prototype. Nevertheless, the acquisition conditions were challenging, and no other integral reproduction of the inner content of the two burial vaults was possible using traditional methods. From an archaeological/forensic point-of-view, the obtained outputs can help assess the general conditions of burial spaces and their content. For instance, the results obtained after the digital recording phase of the first burial vault showed the presence of debris mixed with the human bones and an element from the vault partially detached. Observing these features can help better estimate the overall extension of the human remains and also obtain some clues about the taphonomic effects within the grave.

The results are also strongly dependent on the characteristics of each recorded part. There are variables such as the size of the existent breaches/entrances, the overall size of the closed space, the extent of the space between the structure and the human remains, and their position inside the area that cannot be estimated. Multiple factors heavily influence the success of the recording phase. However, the method shown here also has a good chance of success in challenging situations.

The extraction of the frames from the video is another crucial step. Although the overlap between different frames extracted from a video is generally guaranteed, the ground sampling distance (GSD) may vary significantly depending on (i) the geometry of the surveyed space and (ii) the way the borescope is inserted and moved inside the space. Identifying key points and matching among 360° images requires a similar GSD between consecutive frames capturing the same area. Indeed, a sudden change of GSD may prevent the identification of common points (tie points) and may result in an incorrect orientation of the images. A very high sampling rate of the frames may determine, on the one hand, an overburden of data to be processed, slowing down the photogrammetric reconstruction. On the other hand, a reduced baseline among images can worsen the precision of 3D tie points. For these reasons, the sampling rate selection is a trade-off between two opposing trends.

After some tests, a sampling rate of 1Hz was considered the most suitable for most experiments presented in this paper. Generally, it is recommended to use a sampling rate among frames of a maximum of a few seconds to improve image orientation and dense matching. In addition, if the recording of the borescope data is extended outside of the buried chamber, it is recommended to significantly reduce the insertion speed through the breach. Further selection criteria based on the quality of the frames (i.e., avoiding low-quality and blurred frames) as well as on the similarity of the frames were not implemented in this work and will be tested in the future.

5. Conclusions

This paper described a novel method for the digital documentation of confined spaces, based on a 360° borescope prototype with an illumination system based on adjustable LEDs. Digital photogrammetry was then used for documenting human remains in narrow spaces.

Documenting tiny spaces (a few decimeters) makes image acquisition extremely difficult. In the case of the burial vaults, the size of the breaches was sufficient only to introduce the prototype and to control it from the outside.

The results showed that the gear and the approach used can certainly be applied in archaeological contexts, especially in underground burial contexts in churches or other buildings; forensic applications in similar environments can also gain advantages.

The portable lighting system and the borescope prototype provided promising results in challenging situations, notwithstanding several aspects that can be improved to obtain a better prototype. This was a rather reliable solution, especially when other solutions for data acquisition (such as laser scanning or traditional photogrammetry) were not usable. Several issues remain and the whole system can be improved, including hardware and software components. The flares that are sometimes present in the frames can be a relevant problem if not properly managed, and the correct setting of the entire gear is necessary before any acquisition. Some issues were found in areas documented with the camera close to the object (i.e., less than 0.1 m). The parallax between the lenses also becomes relevant in terms of metric accuracy. After several experiments, the authors believe the metric accuracy is not better than the centimeter level. Other errors could be generated for error propagation in the case of irregular and long trajectories inside the narrow space. However, the resolution of the final output can be better than the millimeter level. The user must know the differences in metric accuracy (in a more photogrammetric sense) and resolution regarding the camera pixel projected on the surfaces.

The photogrammetric outputs are sometimes incomplete, especially in the darkest corners. Despite these constraints, this approach can give an essential overview of the content of underground burials or covered structures that are otherwise completely hidden from sight. The large availability of the elements comprising the borescope prototype and its general low-cost approach make it reproducible and improvable for other similar purposes.

The proposed 360° borescope prototype can be enhanced in many different ways. Currently, results were achieved by combining sensors and lights available on the commercial market as standalone products (i.e., a commercial 360° camera, a set of LED strips cut and powered with an external battery). Creating a complete compact system designed explicitly for only such applications is beyond the scope of this work, notwithstanding other sensors that can be additionally integrated to support image acquisition and processing (e.g., MEMs sensors to provide camera attitude). The camera was also inserted inside complex spaces using different telescopic and orientable pole typologies. Future work can also be related to developing flexible and telescopic supports or tubes that allow the camera to inspect the areas better.

The 360° borescope prototype can also be used as a standard tool for visual inspection, i.e., without further photogrammetric processing. In this case, no specific knowledge of photogrammetric processing solution is required, making the method available to users interested in acquiring a 360° video.

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