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The possibility of using close-range photogrammetry in the inventory of historic complex basements - case study

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Abstract: In the community, historical objects play the role of witness to past history. Due to that fact, it is necessary to preserve and reconstruct cultural heritage objects and sites for the future generation. Photogrammetric methods have been widely applied for this purpose for many years. Nowadays, Terrestrial Laser Scanning (TLS; range-based method), due to its advantages such as speed of data acquisition, high accuracy and independence from light conditions, is increasingly used in the inventory of complex historic buildings. Despite this, the development of modern image processing methods, i.e. Structure-from-Motion (SfM) and Multi-View Stereo (MVS), has meant that close-range photogrammetric techniques are still competitive with TLS. The article aimed to present the possibility of using close-range photogrammetry to inventory historic complex basements. Laser scanning was performed as part of the measurements (with a Z+F 5006h scanner), and a series of close-range images were taken with a full-frame non-metric Canon 5D Mark II camera. Based on the combined SfM and MVS methods, a dense point cloud was generated, which in a subsequent data processing step served as the basis for generating 3D models and cross-sections. To assess the quality of the generated documentation, the TLS data were used as ground-truth data, and the shape and cross-section mapping quality was compared. It is evident from the investment presented that the use of close-range photogrammetry methods makes it possible to generate documentation that meets the requirements of architectural studies and similar shape accuracy for historic complex basements.

Keywords: close-range photogrammetry; cross-sections; cultural heritage; MVS, SfM, terrestrial laser scanning

1. Introduction

The photogrammetric architectural inventory is intended to accurately represent the technical and functional structure, topological relationships and decoration of a single architectural object, its parts or an ensemble of objects [1–6]. Photogrammetric methods have an ever-growing application in the inventory of historic buildings for conservation purposes. Thanks to the photogrammetric approach, a model of the object can be easily presented, and restoration or design work can be planned on it [7]. Close-range photogrammetry is used in the measurement of interiors, often including the modelling of architectural details (vaults, portals) and sculptures. Close-range photogrammetry that products include vector drawings, orthoimages or 3D models is widely used in monument inventory [8–11].

This investigation aims to use the close-range images approach in the inventory of the historic complex basements in the Royal Castel in Warsaw. In this investigation, the following issues are discussed: (1) the quality of images orientation, (2) the comparison of the quality of dense point cloud obtained from image-based techniques and Terrestrial Laser Scanning (TLS), (3) the comparison of the vector drawing obtained from TLS and close-range images and (4) integration with the archival scanned paper documentation. The results of the presented investigation show that utilisation of the close-range photogrammetric method for 3D shape reconstruction allows for obtaining documentation comparable with the TLS technique

2. The methodology of photogrammetric surveying of cultural heritage objects

Photogrammetry uses digital images acquired by recording radiation through a photosensitive array. The result is the information about the shape, size and position of the object under study [12]. Therefore, the choice of the proper sensor and associated equipment fundamentally affects the subsequent quality of the final documentation. To obtain geometrically correct results, it is worth paying attention to, among other things, the resolution of the camera, the choice of lens is based on the focal length, for which the angle of view decreases proportionally with an increase in its value,
e.g. for a building, the widest possible angle of view should be recorded, which is equal to a low focal length, while when examining details, capturing a wide angle is not so required. It is worth mentioning that lenses with extremely wide angles do not have distortion correction, which results in image distortion; these are so-called fisheye lenses. Lenses with fixed focal length values are preferred for photogrammetric measurements because, in zoom lenses, there is the possibility of changing the focal length during the measurement, which significantly reduces the accuracy of determining the elements of internal orientation and the final accuracy of generated documentation (it affect on the scale of the final model). Information on the calibration of the camera-lens combination for each focus setting used is needed. It is recommended to take a photo of the calibration screen with each lens or camera used. It is also important to remember to use a so-called ColorChecker, a standardised colour chart for each successive frame sequence [13].

In order to carry out photogrammetric measurements, it is necessary to design the image network that is a critical factor in image-based 3D shape reconstruction and data processing, especially in the application of using the combined Structure-from-Motion/MulltiView Stereo methods [11,14,15] and photogrammetric control points network [16]. Multiple approaches for photogrammetric image network design have been proposed [14,17,18], but most of them rely on the general rules proposed by Fraser [19], based on the prior knowledge about the measured object and several factors:

- The base-to-depth (B/D) ratio, also called the base-to-height (B/H) ratio, allows defining the accuracy of point/points determination. The following assumption is being made: the network accuracy increases when this ratio increases when using convergent images rather than images with parallel optical axes [19],
- The number of acquired images at which point is measured. The accuracy improves significantly with the number of images in which a point appears; however, measuring points on more than 4 images does not significantly affect accuracy [9],
- The number of measured points in each image, where the accuracy increases with the number of measured points per image. However, the increase is insignificant if the geometric configuration is strong and the measured points are well-defined (such as targets) and well-distributed in the image. In addition, this also applies to the control point utilised [9],
- The image resolution, where, for natural features, the accuracy improves significantly with increasing image resolution, while this improvement is less significant for well-defined, largely resolved targets [20].

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For correct and accurate 3D shape reconstruction, another critical aspect that should be considered is camera position determination, which depends on the object of measurement (Fig.2.). It is necessary to guarantee a frontal overlap of approximately 80% and a side overlap of approximately 60%. Additionally, images should be taken at a distance of half the height of the object of measurement from it. It is necessary to take photos on which two adjacent corners of the object are visible to improve the quality of the final bundle adjustment [13].

Another significant element to be considered when planning and preparing photogrammetric surveys is the preparation and distribution of photogrammetric control points. It is assumed that control points (in the form of, among others, spherical discs, paper discs, etc.) should be contrasting and easily identified with high accuracy. To ensure the correct images adjustment, control points should be distributed over the site, both in the X and Y directions and in the Z direction. Some configurations of warp point placement do not provide a unique solution. For example, if the points are placed on a line, there is then one degree of freedom left, i.e. the model can be rotated around this line [21]. In the case of an enclosed room, points should be placed so as not to damage the object to be measured if it is not possible to adequately place points directly on the walls, on other elements of the object, or place them on tripods to ensure that the measurements are carried out appropriately. When developing images where the number of control points may not be sufficient, unambiguous features of the object can be taken as control points during the matching process.

When taking digital photo measurements in an enclosed room, the problem of adequate room illumination arises, which may be due to a shortage of light or excessive light resulting from the location of a window or artificial lighting. If it is not possible to choose the right time of day, it is necessary to use specialised photographic lighting equipment and select it accordingly. These include studio photography lamps and light diffusers (so-called softboxes) or diffusing umbrellas. The use of this equipment will allow even illumination of the subject to be photographed, which will provide high-quality images as input to the study. Studio lamps provide uniform brightness of the photo, which will not always be achieved using a lamp built into the camera or a lamp mounted directly to the camera (so-called reporter lamp). Due to the mainly wide-angle lenses used for photogrammetric measurements, these lamps will not illuminate the whole frame of the photo, especially when the interior of the photographed object is complicated (on a plan other than a square or rectangle), which involves shadowed areas. Suppose the exposure of the frame is uneven and difficult. In that case, it is necessary to take photos using the HDR technique (High Dynamic Range Imaging - a technique in photography that consists of taking several exposures of the same frame, some of which are underexposed and some overexposed. It allows for obtaining an image of a scene characterised by a large tonal range [13].

3. Materials and Methods

The proposed method of close-range images processing is a multi-stage process; it consists of (I) Photogrammetric control point determination, (II) TLS data acquisition and pre-processing – generation of ground-truth data, (III) close-range images acquisition and processing and (IV) quality assessment and final documentation generation. Figure 2 presents the diagram of the research work and experiments performed.

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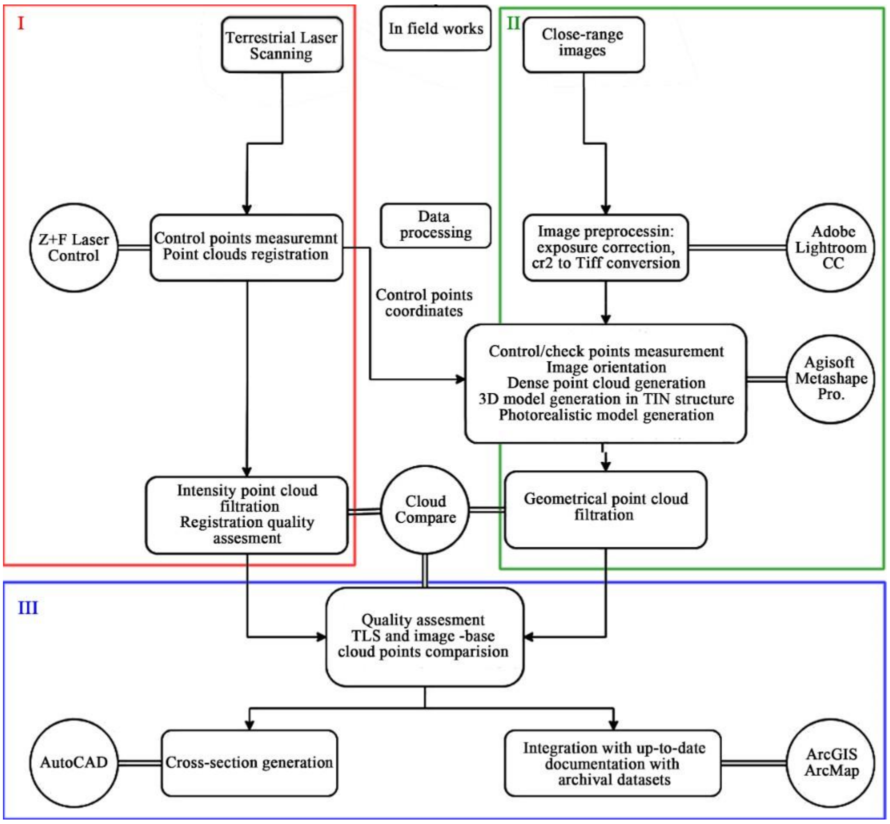

Figure 1. The diagram of the proposed method of documentation generation

(I) Photogrammetric control points determination

The pre-measurement stage was the planning and distributing of the photogrammetric control points used for image orientation with the Structure-from-Motion approach and TLS point cloud registration. To ensure the millimetre accuracy of the data orientation, the control points should be located at different heights and evenly across the entire study area. As reference points, the black and white crosses were chosen.

(II) TLS data acquisition and pre-processing – generation of ground-truth data

The laser scanner stations were evenly distributed throughout the historic basement to guarantee the highest possible accuracy while reducing data redundancy and eliminating areas with too low a point cloud resolution or no data. Preparation of ground-truth data consisted of two stages: (1) TLS point cloud registration with the target-based method and (2) two-stage filtering of points with too low laser beam intensity (< 0.5%) and too high laser beam reflection power (> 99%) with geometrical filtering using SoR (Statistical Outlier Removal) method [22]. TLS point cloud registration and post- intensity point cloud filtering were performed in Z+F Laser Control software. Geometric filtering of the point clouds was performed in CloudCompare software.

(III) Close-range images acquisition and processing

Close-range images were processed in Agisoft Metashape software. In the first processing step, the images were orientated using the Structure-from-Motion method [23]. As a result of this data processing, the non-metric camera calibration parameters and the external orientation elements of the images were determined. The combined images were used in the next step to generate a dense point cloud using the Multi-View Stereo [14,24] method based on the Semi-Global matching algorithm [25].

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(IV) Quality assessment and final documentation generation

A comparison based on distance analysis between point clouds from the TLS and cross-sectional crosstalk comparison was chosen to assess the geometric quality of the point cloud obtained from dense close-range image matching. This approach enabled a quantitative analysis and a visual analysis of the correctness of the generated cross-sections. Finally, point clouds were used to generate photorealistic 3D models of the individual basement sections and cross-sections.

3.1. Test site description

The object of the photogrammetric architectural documentation study is the four basement rooms located in the Tin Roof Palace, which lies at the foot of the Royal Castle in Warsaw (Fig. 2a).

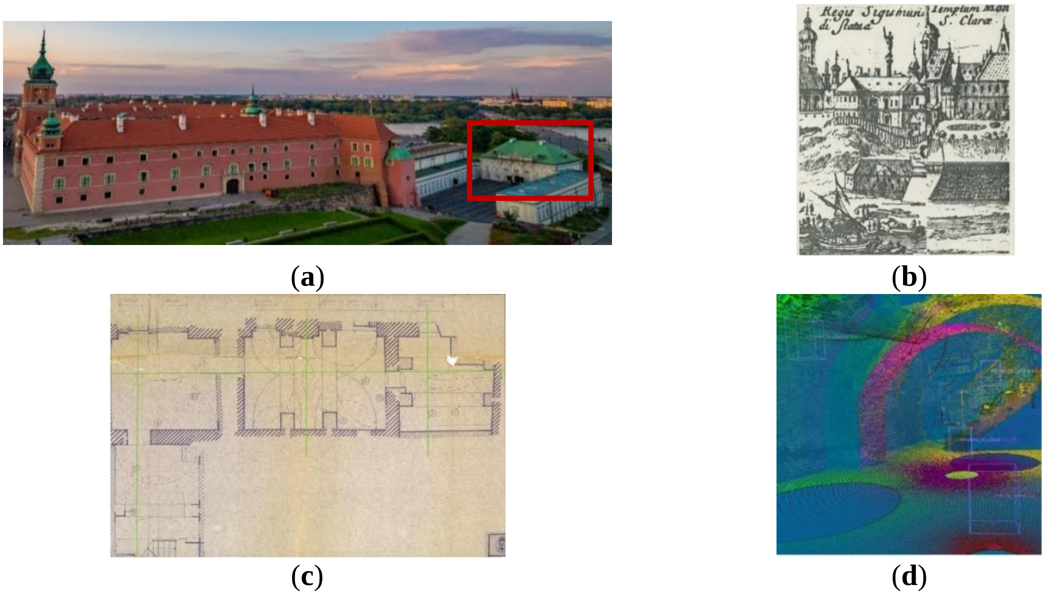

Figure 2. (a) The view of the Royal Castle in Warsaw with marked Tin Roof Palace (red rectangle), (b) Reffus tenement, the fragment of the Panorama of Warsaw from the Praga side - 1656 year (c) The archival plan of the cellar chambers, (d) The example view of the point cloud from one scanner position.

Three of the cellar chambers, arranged in a row, constitute the first tract of the palace to the east. In contrast, the fourth is adjacent to them in the second tract by the northern wall of the palace (Fig.2b,c). The rooms of the eastern lot are remnants of the first known building on this site - the house of Lawrence Reffus, which can be confirmed by comparing the shape of the building and the position of the openings in the outer walls with the drawing made according to Eric Dahlberg's drawing (Fig.2d).

That these are the remains of the Reffus house is also evidenced by the royal document granting the plot to the royal blacksmith. The dimensions shown in the document faithfully match the size of the cellars preserved under the present courtyard of the Tin-Roof Palace.

Research carried out in 1992 by the architect Tomasz Liniecki indicates that the construction cycle of the eastern tract chambers was monophasic. This is evidenced by the remains of a uniform eastern front wall, built on a foundation of large stone blocks, extending the entire building length. This wall is associated with the vaults of the large central chamber and the smaller southern chamber. The rear walls of the central and northern chambers and the walls separating the chambers from each other also appear to belong to this phase. They can be tentatively dated to the mid-17th century. The vaulted ceiling and the front wall of the northern corner chamber were added to the walls built in phase one during their repair after significant damage. The open cellar chamber in the middle course of the palace was built slightly later - the material used for the vault suggests the first half of the 18th century

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3.2. The sensors used

It was decided to use a Z+F 5006h scanner to acquire point clouds from terrestrial laser scanning, with angular resolution 360º/320º and scanning resolution of 4 mm at 10 m. The non-metric Canon 6D EOS camera was used to acquire the close-range images, which features a full-frame 36 x 24 mm CMOS sensor with a resolution of 20.2 MP and a DIGIC 5+ processor. The lens used was Canon 16- 35mm f 2.8 L III USM, and images were taken using the 24mm focal length. The selected lens allowed the focal length to be locked, avoiding accidentally changing the focal length. Due to the poor lighting indoors, it was necessary to use studio lamps on tripods were used for this purpose, along with radiation-diffusing softboxes. The softboxes used unfortunately proved to be too large in some cases and made it challenging to obtain geometrically correct images; the measurement was carried out using reporters' lamps with a diffusing cap.

4. Results

Control points were distributed in the first stage of data preparation, but this has not been without problems. This arose from the condition of the walls of the rooms. It was not possible to stick the photogrammetric marks to the walls using various types of tape, as this was associated with dust and the crumbling mortar with which the bricks are cemented bricks. Due to the condition of the vaults, bricks were used that were in the hall and taped all around. Photogrammetric control points were placed on installation elements and pipes. Nails protruding from the walls, securing the opening leading to the outside and metal frames were used to reinforce the passages to the next chambers

Figure 3. The example of control points distribution

4.1. Ground-truth data preparation

Table 1 shows the results of the data orientation process, and Figure 4 shows the point clouds combined into one dataset after the filtering process.

Table 1. The Statistics of the TLS registration process carried out for the whole and individual rooms separately

Parameter	All rooms	Room no. 1	Room no. 2	Room no. 3	Room no.4
Total number of control points on point clouds	115	26	30	43	14
Number of disabled targets	7	2	1	1	0
Average deviation [mm]	2.9	2.2	2.7	2.5	2.1
RMSE [mm]	1.4	1.0	1.4	1.2	0.8
Maximum deviations	6.3	4.5	6.6	6.1	3.7

From the presented TLS registration accuracy results (Tab. 1), it can be seen that the point clouds were oriented with similar accuracy for all rooms. RMSE values range from 0.8 mm to 1.4, and the orientation error for all point clouds was 1.4 mm. When analysing the maximum deviation on the puncta, it should be noted that the smaller ones were obtained for Rooms no. 1 and 4, for which the distances between scans and points were smaller than for Rooms no. 2 and 3.

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Figure 4. The sketch of TLS positions is marked as red dots

The TLS point cloud registration results demonstrate the data registration's high accuracy and oriented point clouds can be used to analyse further the suitability of the close-range photogrammetry method for the inventory of historic basements. Figure 4 shows a sketch of the terrestrial laser scanning positions.

4.2. Close-range images orientation

In the first stage of close-range images processing, photos were divided the input data into four groups (so-called chunks) related to individual basement rooms. To co-registered images with the TLS data set, it was decided to use the coordinates of control points from laser scanning point clouds. The Structure-from-Motion approach implemented in the Agisoft Metashape software was used for the image orientation. In Table 2, the result of the bundle adjustment process on control and check points with a relative orientation was shown.

Table 2. This results of the Structure-from-Motion process.

Celler no.	No. of images	Reprojection error [pix]	Control points				Check points			
			RMSE X [mm]	RMSE Y [mm]	RMSE Z [mm]	RMSE L [mm]	RMSE X [mm]	RMSE Y [mm]	RMSE Z [mm]	RMSE L [mm]
1	85	1.4	2.5	3.0	2.1	4.4	4.4	3.4	5.4	5.3
2	62	1.4	2.4	3.6	4.1	6.0	3.5	1.5	5.8	6.2
3	115	1.0	1.1	1.6	1.2	2.2	4.3	2.3	1.5	6.4
4	127	1.3	1.7	2.4	2.1	4.6	2.5	2.8	3.1	4.7

Table 2 shows the accuracy of the SfM process with:

- The reprojection error value, which is responsible for the quality of the relative images orientation,
- The RMSE values at the control points, which refer to the accuracy of the bundle adjustment process – photogrammetric model generation,
- The RMSE at the check points, which are not used in the bundle adjustment process and are indicative of the accuracy of the fit of the images in the external reference system, as accuracy indicators.

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The reprojection error values for the rooms are similar and do not exceed 1.4 pixels. This shows that the images were correctly relatively oriented, considering that a non-metric measuring camera was used. When analysing the RMSE values at the control and check points for each room separately, it can be seen that they are close to each other, which indicates that the bundle adjustment carried out is correct. Figure 5 shows a schematic of the image distribution and the cloud of tie points detected by the SfM process.

Figure 5. The arrangement of individual images against the tie point cloud for each room separately - images marked as a as blue rectangle

The next step in image processing was to generate a dense point cloud. For this purpose, the "Build Dense Cloud" with a quality selection of "High" related to the 1/4 resolution of image was chosen. Due to the lack of sharp edges, quality and structure of the object, the filtration parameter "Mild" was chosen. In order to regularise the point cloud, the subsampling with the grid sampling of 2 mm was applied. In Figure 6, an example of the final point is shown.

Figure 6. The visualisation of the resulting dense point clouds from close-range images

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4.3. *Integration of close-range photogrammetry with archival documentation*

The ArcGIS software integrated the image dense point clouds with the archival architectural vector from 1992. For this purpose, a cross-section was taken at approximately 0.5 m from the ground and exported to las format. Based on the generated point clouds, the scanned vector map was georeferenced. The georeferenced vector drawing was used to generate cross-sections at the locations of the archived architectural works (Fig. 7).

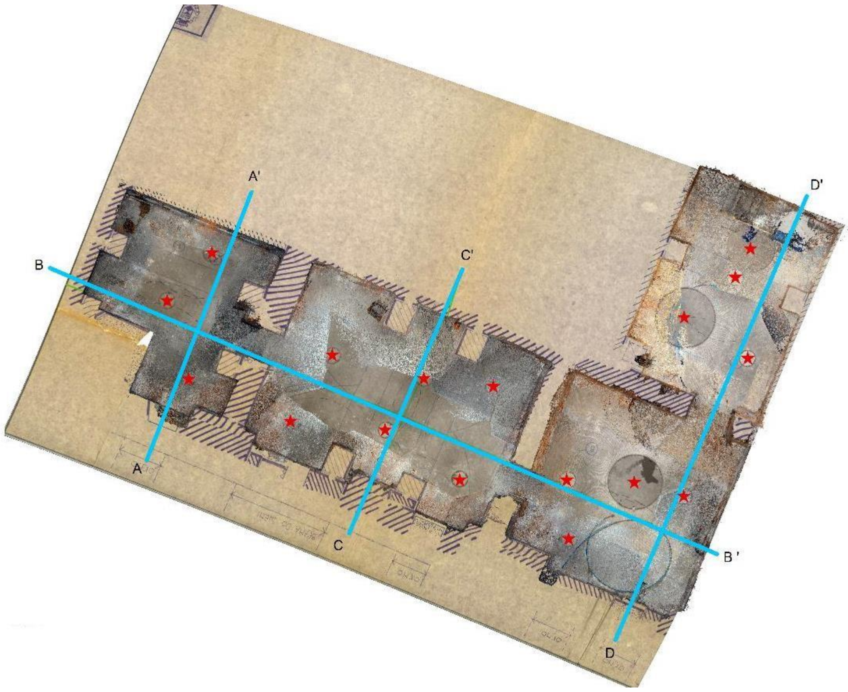

Figure 7. The result of the point cloud integration with archival vector drawing. Blue lines determine the position of cross-sections.

5. Discussion

The assessment of the suitability of utilising close-range photogrammetry in the inventory of historic complex basements involved (1) evaluating the accuracy of shape representation (point clouds) compared to Terrestrial Laser Scanning and (2) visually assessing the correctness of cross- section generation.

5.1. *3D shape assessment – cloud-to-cloud distance analysis*

The comparisons were carried out between clouds acquired from close-range images and selected TLS data (Fig. 8 – 11).

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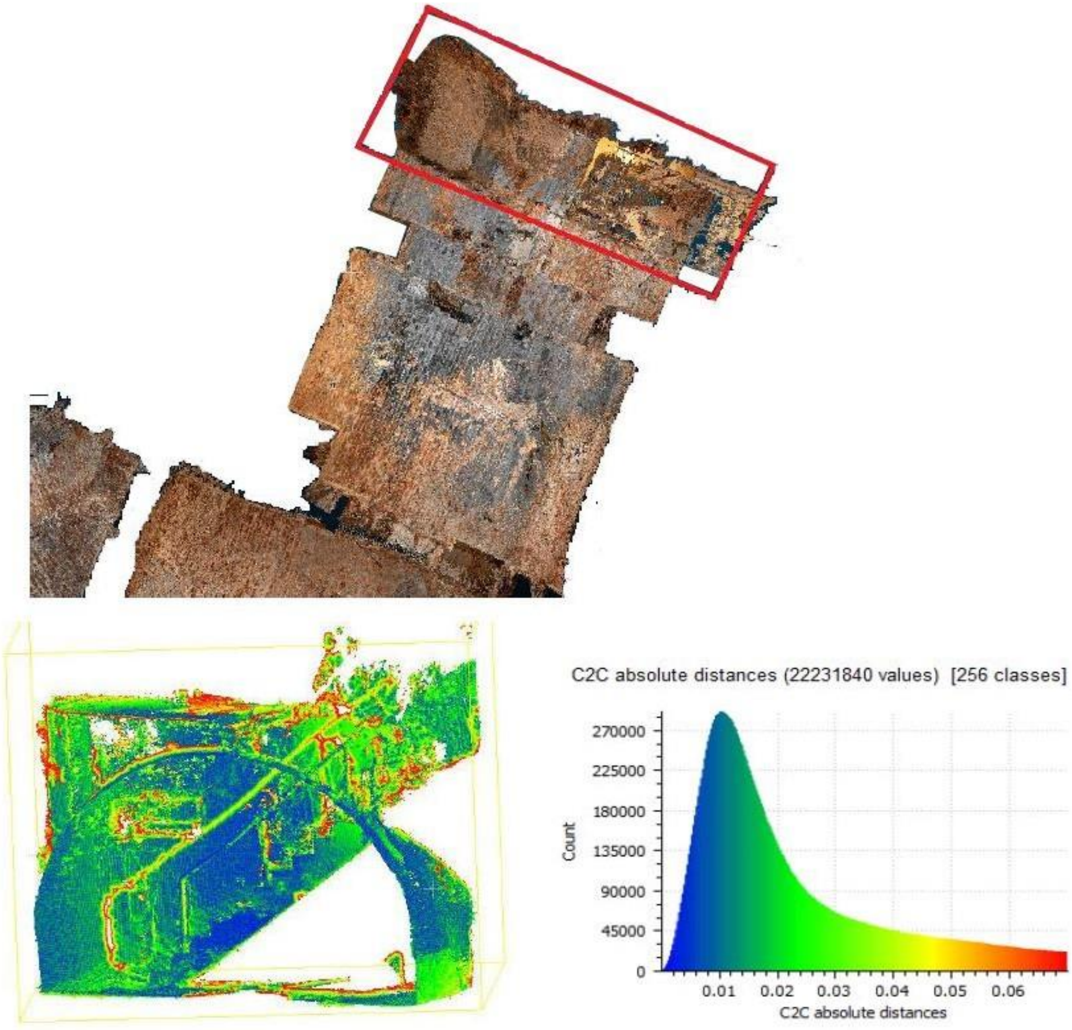

Figure 8. The result of the comparison of clouds from close-range images and scanning data in room 1

The area selected in room 1 (Fig.8) shows deficiencies in the cloud acquired from scanning in places where the laser beam could not reach (red colour). At the same time, measurement by ground- based photography was possible. Maximum deviations between point clouds reach 6 cm, the peak of the histogram was 1.1 cm, and the shape of the histogram is approximately chi-square, demonstrating the shape determination's correctness.

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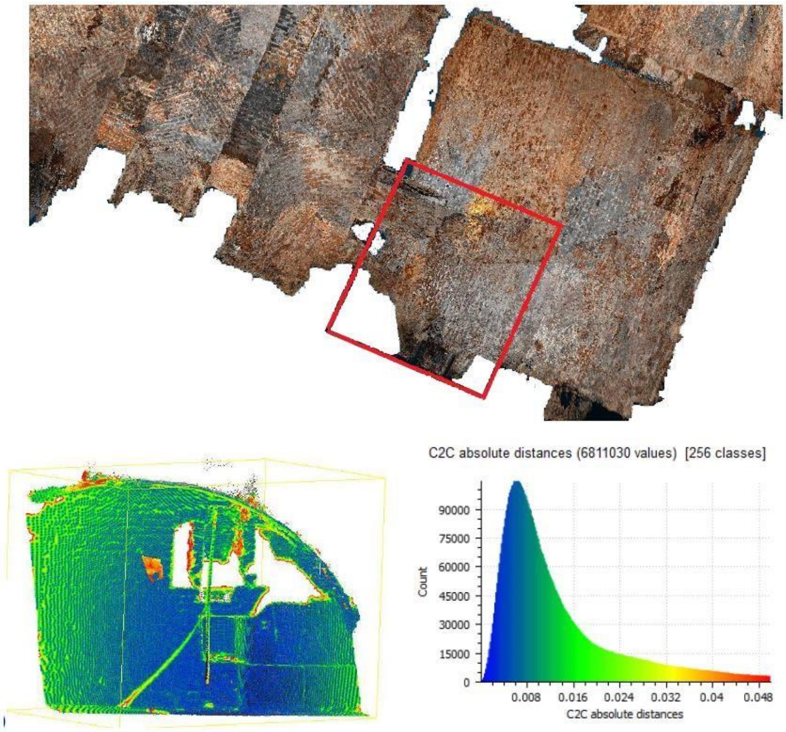

Figure 9. The result of the comparison of clouds from close-range images and scanning data in room 2

Similar to the results obtained for room 1, the apparent gaps in the deviation model indicate the poor accuracy of the representation of this area of the TLS point cloud. Maximum deviations reach 3 cm, the peak is 1 cm, and the histogram approximates the shape of a chi-square distribution.

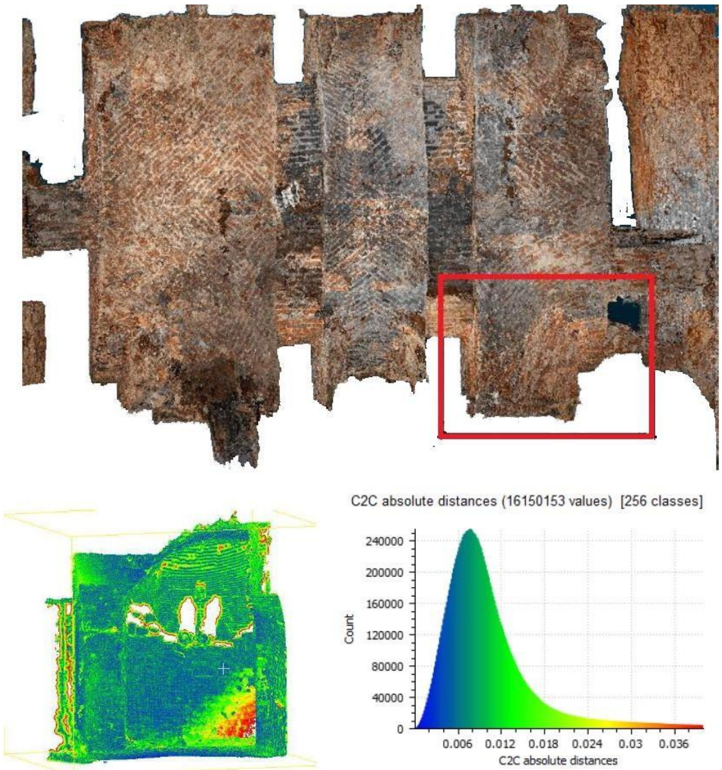

Figure 10. The result of the comparison of clouds from close-range images and scanning data in room 3

For room number 3, the area with the installations was selected (Fig. 10). Again, the cloud from the photographs was taken as a reference. In this section, the maximum deviations are about 4 cm for

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the corner of the room and about 1 cm for the rest. The peak of the histogram was 1.1 cm, and the shape of the histogram is approximately chi-square, demonstrating the shape determination's correctness.

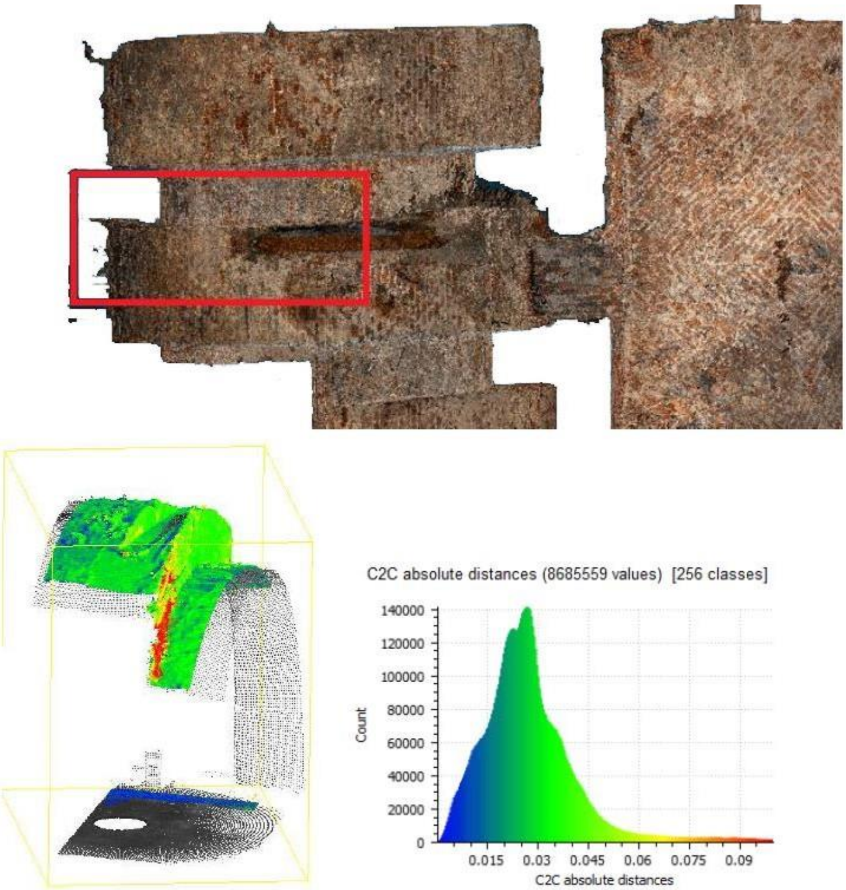

Figure 11. The result of the comparison of clouds from close-range images and scanning data in room 3

In room number 4, a fragment of the arch was selected together with the architectural detail on the vault (Fig.11) Both the processed data from TLS and close-range images allow for the fully reproduced examined fragment. However, deviations of 9 cm are observed in the area of the vault break. In comparison, in the remaining area, the deviations are in the range of 1.5 - 3.5 cm, which may be due to the smaller number of control points, its distribution in this room (only 4) and the lower accuracy of data registration.

Summarising the results obtained from the analysis of the quality of 3D shape mapping, it can be concluded that methods based on the close-range photogrammetry approach enable shape mapping in places that are difficult to access for TLS, thus solving problems that occur with TLS measurements. Comparing the deviations between point clouds, it can be seen that for 3 of the 4 rooms, the histograms have an approximate chi-square distribution, which indicates the correctness of the generated point cloud. Only in the case of room 4 were worse results obtained due to the smaller number of control points and how they were placed, which significantly affected the image orientation. Despite this, the acquired results meet the accuracy requirements for architectural documentation.

5.2. Cross-section analysis

Nowadays, architectural inventory involves preparing very detailed object documentation, including cross-sections, floor plans, sanitary and electrical fittings, and plumbing inside and outside

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the building, and mapping the damaged areas [26]. For this reason, it was decided to compare the shape of the cross-sections marked in Figure 7 (Fig. 12 - 15).

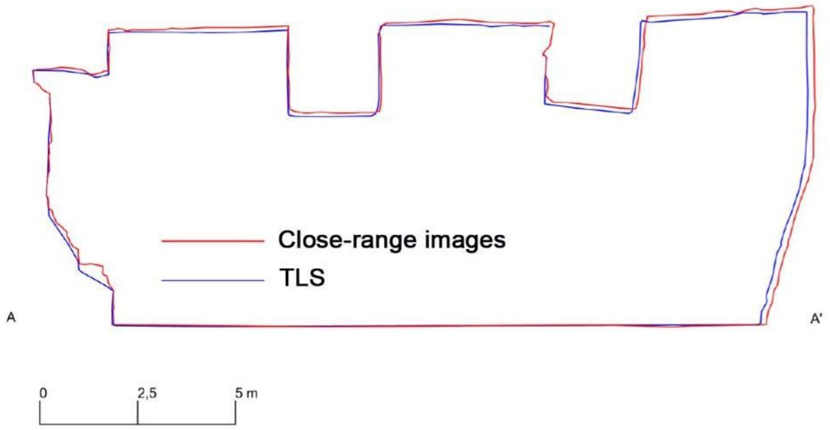

Figure 12. The cross-section A-A'

When comparing cross-sections A-A', changes in the shape of the detail representation can be seen. This is due to factors affecting the accuracy of the generated point cloud, i.e. the influence of self-calibration for a group of images, which changes the scale, the accuracy of the images orientation and the correctness of the dense image matching process. The mapped shape should be considered acceptable despite the visible differences in shape, as the maximum distances between vector drawings do not exceed 2 cm. It should be noted that this cross-section was made on the basis of the room's 4 point cloud, which had a lower accuracy of shape representation (Fig. 11).

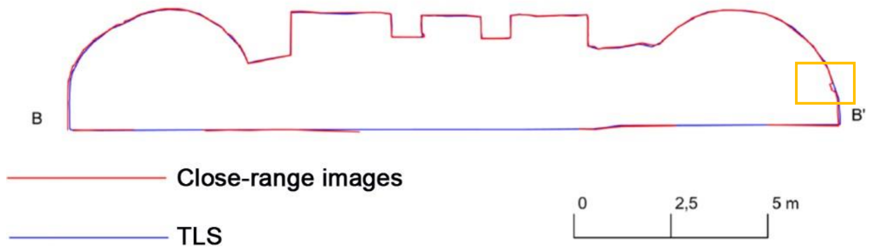

Figure 13. The cross-section B-B'

For cross-section B-B' (passing through rooms 2 - 4), better results were obtained than for A - A'. This is due to the better quality of the point cloud from the close-range images and the higher accuracy of the photo orientation. The most significant deviations were obtained from the section on the right (marked yellow), which was 0.6 cm. Similar results were also obtained for the C-C' cross- section (Fig. 14)

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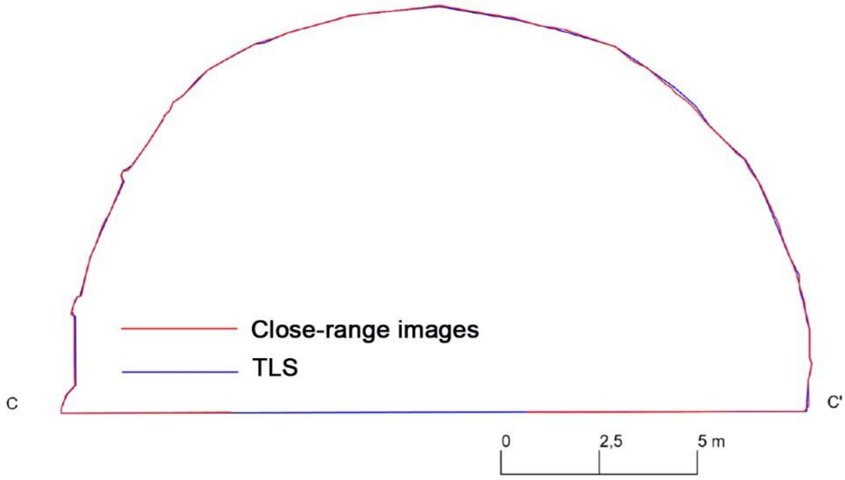

Figure 14. The cross-section C-C'

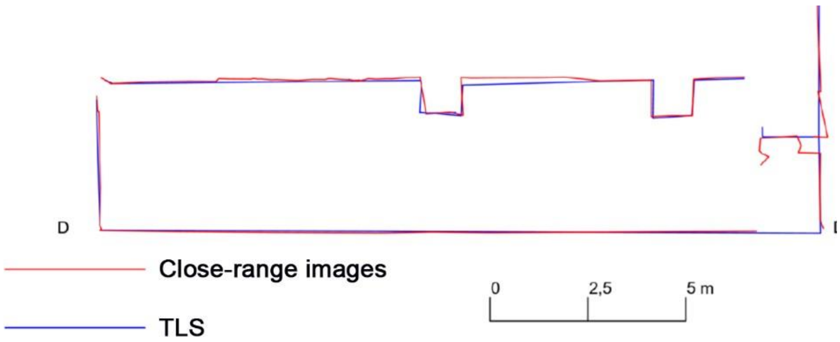

Figure 14. The cross-section D-D'

When analysing the differences between cross-sections D-D' (Fig. 15), similar relationships can be observed for cross-sections A-A'. Despite this, the deviations do not exceed 2 cm, so the documentation generated based on these data can also be regarded (as in the case of cross-sections A- A') as acceptable.

6. Conclusions

This work aimed to generate architectural documentation for four rooms of the historic basement using close-range photogrammetric techniques. Due to the condition of the building, difficulties arose in establishing the photogrammetric network; the signal control points were distributed in an untypical location, which affected the accuracy of the point representation. The laser scanning data was processed in the Z+F Laser Control programme and the data from terrestrial photographs in Agisoft Metashape Professional. Acquired point clouds were compared and analysed using Cloud Compare and further processed to generate architectural documentation in the form of four cross-sections of the point.

In summary, the resulting study products reflect the current state of the surveyed, meet the accuracy conditions for architectural documentation and can serve as a basis for planning any works on the site. An important in this type of measurement is the integration of methods to fill in data gaps. The documentation produced as part of this work has been added to the archives of the Royal Castle in Warsaw.

Authors Contributions: J.M. and K.D. organised the conceptualisation of the idea and the methodology employed in this paper. Following that, J.M and K.D. carried out the experimental design. K.D. worked on the

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data acquisition, J.M. carried out the original writing and draft preparation. J.M., K.D. undertook the data analysis. All authors have read and agreed to the published version of the manuscript.

Conflicts of Interest: The authors declare no conflict of interest.

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