Article

Integration of multi-temporal photogrammetric images in conservation work at the Royal Castle in Warsaw

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Abstract: This study presents a comprehensive application of photogrammetry to document the archaeological excavation and restoration of the Justice Tower at the Royal Castle in Warsaw, Poland. By capturing images at various stages of the project, Structure-from-Motion (SfM) and Multi-View Stereo (MVS) techniques were employed to generate detailed 3D models of the Tower's interior. A significant challenge in this research was the integration of multi-temporal data, as the Tower's appearance changed significantly over time. To address this, the TLS-SfM algorithm was utilised to align point clouds from different epochs, ensuring accurate spatial registration. The resulting 3D models provide a rich visual record of the Tower's historical evolution, revealing intricate details of its construction and subsequent modifications. These digital artefacts serve as invaluable tools for archaeologists, historians, and conservators, enabling in-depth analysis, virtual reconstructions, and informed decision-making for future preservation efforts. By demonstrating the power of photogrammetry in capturing and analysing complex archaeological sites, this study contributes to the field of heritage documentation and digital archaeology.

Keywords: archaeological investigation, MVS, Royal Castle, SfM

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1. Introduction

Architectural documentation derived from archaeological measurements has been utilised for many years in archaeological research. This is primarily due to its ability to quickly and accurately inventory sites while keeping the costs of obtaining geospatial data low. It is important to note that accurate recording and documentation of artefacts and sites facilitate proper subsequent analysis and interpretation. To achieve this, both image-based techniques (passive methods, such as close-range photogrammetry) and range-based methods (active techniques, such as Terrestrial Laser Scanning - TLS) are employed for 3D shape reconstruction (Abbate *et al.,* 2019; Arif and Essa, 2017; Cipriani *et al*., 2019; Grussenmeyer and Yasmine, 2004; Hatzopoulos *et al.,* 2017; Heras et al., 2019; Markiewicz *et al.,* 2017; Remondino and Elhakim, 2006).

Various measurement techniques and sensors are used to inventory heritage sites and archaeological excavations. These include images captured by aerial cameras and those mounted on UAVs (Arif and Essa, 2017; Del Pozo *et al.,* 2017; Grussenmeyer and Yasmine, 2004; Koistinen, 2004; Murtiyoso *et al.,* 2017; Nocerino et al., 2012; Sauerbier and Eisenbeiss, 2010), LIDAR - ALS and TLS (Arif and Essa, 2017; Del Pozo *et al.,* 2017; Drap *et al.,* 2007; Gonizzi Barsanti *et al.,* 2013; Grussenmeyer and Yasmine, 2004; Hatzopoulos *et al.,* 2017; Markiewicz *et al.,* 2017), as well as close-range photogrammetry (Gonizzi Barsanti *et al.,* 2013; Grussenmeyer and Yasmine, 2004; Hatzopoulos *et al.,* 2017; Remondino and El-hakim, 2006).

The research presented in this article continues the archaeological inventory studies conducted at the Royal Castle in the Justice Tower between 2017 and 2019, as outlined in the articles (Markiewicz *et al.,* 2018) and (Bocheńska *et al.,* 2019). The previous papers presented preliminary work on the external side of the Tower and the results of two phases of archaeological excavations inside the Justice Tower. This article provides comprehensive results from the beginning of the work inside the Tower to its completion and the restoration of its original condition. A novel aspect of this article is the presentation of a complete 3D model and the inventory results, along with an extended analysis of data integration accuracy.

2. The history of the Grodzka Tower in Royal Castel in Warsaw – archaeological prospection through years

The Royal Castle in Warsaw is one of the symbols of the Polish capital and the entire country. It once served as a royal residence, a place of parliamentary debates and an administrative centre. Today, it is undoubtedly a cultural entity, serving as a museum.

The rich history of the Royal Castle begins in the 14th century when the Grodzka Tower (formerly the Great Tower) was built. During the reign of King Sigismund III Vasa, the Castle was extended; the building had the shape of a closed pentagon. Unfortunately, in the second half of the 17th century, during the so-called 'Swedish Deluge', it was destroyed. It regained its splendour thanks to King Stanislaw August, who hired artists to rebuild the interiors of the chambers.

The 19th century saw the looting of the Castle, and the following 20th century saw significant bombardments,

during the Second World War. Finally, the Castle was virtually wholly blown up by German troops in 1944. Although much of the Warsaw royal residence was destroyed, remnants such as foundations and basement structures endured, preserving a fragment of its material legacy. Despite its physical absence, the Castle remained prominent in the public consciousness, ultimately driving efforts to restore this significant historical site. The proposed reconstruction became the impetus for extensive investigations, providing a platform to address questions about the site's historical and architectural evolution.

Ironically, the destruction of the Castle enabled an unprecedented opportunity for detailed research. The post-war reconstruction of Warsaw, severely damaged during World War II, offered a rare chance for architects and archaeologists to comprehensively investigate the city's and the Castle's history. However, the political and social contexts of the time influenced the research outcomes, introducing both limitations and complexities. Nevertheless, the endeavour pioneered the integration of expertise across multiple disciplines. For instance, specialists from the Warsaw University of Technology employed photogrammetric techniques during the architectural inventory, while geological drilling was utilised for the first time to analyse cultural layers. These multidisciplinary methodologies laid a substantial groundwork for continued exploration of the Castle's origins.

One critical area of focus was the 14th-century Justice Court Tower, the oldest surviving masonry structure within the Castle complex. Although the Tower and its surroundings were studied during the initial reconstruction period, the research scope was narrow, leaving unresolved questions about its structural features and relationship to other components of the Castle. Renewed archaeological investigations in 2017–2019, coinciding with the Tower's renovation, sought to address these gaps.

This recent research included excavations within the Tower's interior and along its western exterior wall, aiming to elucidate its foundational design and the construction technologies utilised. The concurrent construction activities imposed significant time constraints, necessitating the adoption of rapid documentation techniques. The project was structured to generate comprehensive digital documentation incrementally at different stages of the excavation. Challenges included varying weather conditions, restricted accessibility to certain features, and the requirement to deploy diverse documentation methodologies and equipment. Despite these constraints, the research employed a flexible, methodologically rigorous approach, advancing the understanding of the Castle's historical and architectural significance under complex and dynamic conditions.

The reconstruction process lasted from 1971, when the decision to rebuild was taken, until 2019 - the end of the reconstruction of the entire castle complex.

The prison cellar, which is the object of the research, lies on the lowest floor of the Castle Tower. It is a room made of brick with walls 3m thick and measuring 4.6m x 4.6m. The basement survived the blowing up of the Castle in 1944. Only the ceiling and partially the faces of the walls were destroyed. Thus, the 117 engravers were found there, carved into the walls by prisoners held in the prison probably in the 17th century; one drawing shows the date 1630, which is a priceless monument of the Royal Castle (History of the Royal Castle in Warsaw, Basements of the Royal Castle in Warsaw, 2022).

3. The archaeological investigations in Justice Tower – photogrammetric surveying

3.1. The main assumptions for dividing the archaeological work and its inventory into epochs

Two distinct measurement techniques were employed to conduct the geodetic and photogrammetric measurements: classical surveying utilising total-station Leica 1201+, and close-range imagery captured using a Canon 5D Mark II in conjunction with a cost-grade Olympus C-5050Z. Two specialised teams executed the research: surveyors and photogrammetrists from the Warsaw University of Technology, alongside a team of trained archaeologists from the Royal Castle in Warsaw. The investigation was organised into four distinct phases:

- Epoch 0 (2018 year) - To document the condition before the commencement of archaeological work, a series of photographs of the "original floor" were captured using an image-based approach and a Canon 5D Mark II camera. Due to the inability to establish photogrammetric control points, it was decided to perform orientation and generate dense point clouds within a local reference system.
- Epoch 1 (2018 year) - The first stage (intermediate phase of archaeological excavations) encompassed the entire interior area of the Justice Tower. For this area, it was possible to establish and measure a photogrammetric reference network. Like Epoch 0, the images were captured using a Canon 5D Mark II camera.

- Epoch 2 (2018 year) - This phase of the archaeological work focused on the lowest excavation level and marked the final stage before reconstruction and the return to the original state. Due to health and safety regulations and the specific requirements for work at this stage, the photographs were taken by staff from the Royal Castle in Warsaw using a low-cost Olympus C-5050Z camera.
- Epoch 3 (2019 year) – the final phase of the work involved restoring the Justice Tower to its condition before the commencement of the archaeological excavations. The only modification was replacing the original solid floor with a glass floor to highlight the historic original stones forming the so-called "old floor." This last phase was also documented using the Canon 5D Mark II camera. It is important to note that, as in previous stages, it was impossible to establish photogrammetric control points.

3.2. Data processing methodology

The proposed approach to data processing was a multi-stage process consisting of the following steps:

- Surveying for control points coordinates the determination

To determine the coordinates of the points within the Tower, the positions located between the outer perimeter of the building and the interior of the Tower were transformed into a reference system aligned with the external vicinity of the Royal Castle. These positions formed a suspended traverse. A three-tripod method was employed, placing three stations—one instrument and two prisms. Measurements were conducted between the stations without altering their relative configuration, ensuring more accurate results and minimising potential errors. Coordinates from the external reference system were transferred to the interior of the Tower, where a photogrammetric network was established. This network's X and Y coordinates were computed using the polar method, while the height (H) was derived using trigonometric levelling. Horizontal and vertical angles and oblique distances were measured in two series to mitigate the risk of gross observational errors. The data for the calculations was averaged from two measurements. This dataset was subsequently used for image orientation.

- The relative orientation of images and the generation of dense point clouds

Structure-from-motion (SfM) and Multi-View Stereo (MVS) algorithms implemented in Agisoft Metashape software were employed to orient the images and generate dense point clouds. During the SfM stage, full-resolution images were used for orientation (Accuracy parameter set to High), while for MVS, half of the full resolution was applied (parameter set to High). These parameters were chosen based on the balance between the accuracy and completeness of the orientation process and the processing time required for generating dense point clouds. Additionally, the images were divided into groups (chunks) based on the photographing distance from the respective walls to ensure correct calibration parameter determination during self-calibration. Finally, all the chunks were relatively registered using the align and merge chunks methods.

- Muti-temporal data registration

As previously mentioned, reference points were only photographed for the group of images from Epoch 1, allowing for the images' external orientation and alignment within the adopted reference system. Therefore, it was necessary to propose a method for mutual orientation of multi-temporal images from different epochs based on the data from Epoch 1. To achieve this, the TLS-SfM method was utilised, involving the identification of tie points on point clouds converted to raster format with an assigned depth map (Fig. 1). A detailed description of the TLS-SfM method is provided in the article *The evaluation of hand-crafted and learned-based features in Terrestrial Laser Scanning-Structure-from-Motion (TLS-SfM) indoor point cloud registration: the case study of cultural heritage objects and public interiors (Markiewicz et al., 2023)*.

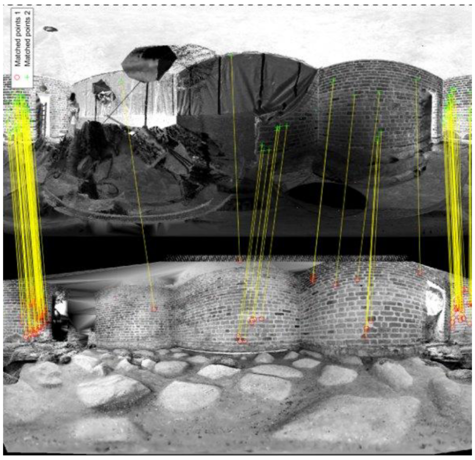


Figure 1. The example of the multi-temporal point clouds converted into the spherical form with detected tie points utilised for relative data orientation (Bocheńska et al., 2019).

- Final documentation generation

The final data processing stage involved generating architectural documentation in the form of photorealistic 3D models. Similarly to the relative image orientation, Agisoft Metashape software was used, employing.

4. Results of the photogrammetric surveying

The process of close-range images orientation was divided into two stages: (1) Relative orientation of image groups for different distances for each wall separately, and (2) Relative orientation of images for all walls. This scheme was proposed for all Epochs. To align all images, it was decided to first merge them into chunks for each wall separately and then combine the chunks into a model of the entire basement. The "Align Chunks" function was used for this process, with the chunks being aligned using the "Point-based" method, allowing the point clouds to align based on all the points.

4.1. Epoch 0

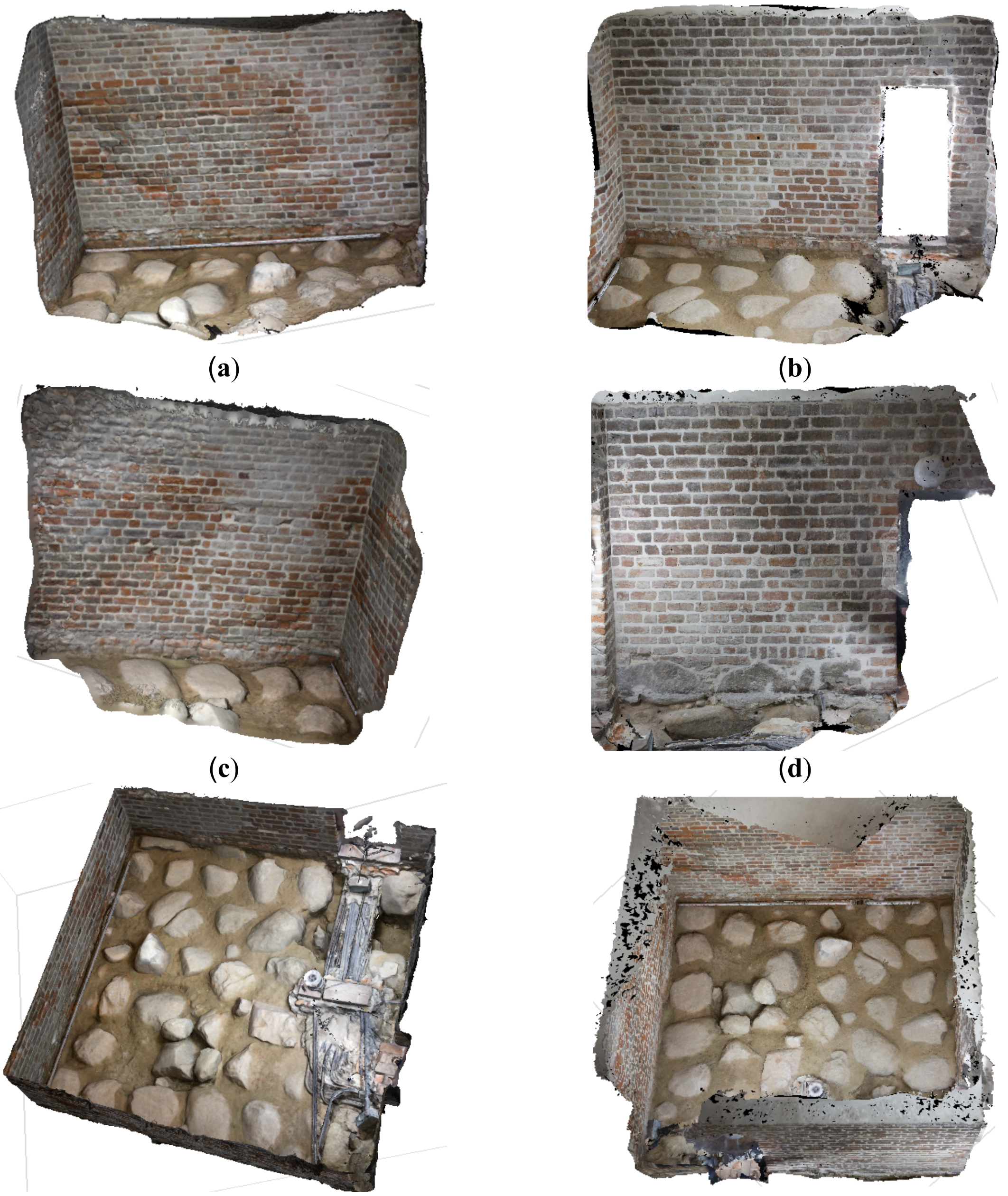
The first stage of data processing involved the orientation of photos for Epoch 0, prior to the commencement of archaeological work. Table 1 presents the basic information regarding the accuracy of photo orientation for individual sections of the room.

Table 1. Analysis of the Number of Images and Reprojection Errors.

Images group name	Reprojection error [pix]
Front	1.2
Right	0.7
Left	0.6
Back	0.4
Floor	1.4

Analysing the number of images and reprojection errors reveals several key observations. The front group, with 51 images, has a reprojection error of 1.2 pixels, showing a moderate number of images and a relatively higher error. The right group, consisting of 14 images, exhibits a reprojection error of 0.7 pixels, indicating better precision with fewer images. Similarly, the left group, with 17 images and a reprojection error of 0.6 pixels, shows slightly better accuracy than the right. The back group, with 16 images and the lowest reprojection error of 0.4 pixels, demonstrates the highest level of alignment despite having fewer images. The floor group, which contains 166 images, has the highest reprojection error of 1.4 pixels, likely due to the greater complexity of aligning a larger number of images over a wider area. In conclusion, smaller, more focused groups tend to show better accuracy. In comparison, larger groups, such as the floor, tend to have higher errors, likely due to the challenge of maintaining precision across a larger dataset.

Figure 2 presents the results of the 3D models generated for Epoch 0 before each wall's commencement of archaeological work separately.



(a) (b)

(c) (d)

(e) (f)

Figure 2. The photorealistic model: (a) the front wall, (b) the right wall, (c) the left wall, (d) the back wall, (e) the floor, and (f) the entire basement before excavation (top-down view) - Epoch 0.

4.2. Epoch 1

In this stage of the work, images of the basement during excavation were available. These images were taken during the second and third weeks of May 2018 (Epoch 1 and 2). Despite the short time span between the two image series, the basement had undergone significant changes, which led to the processing of two separate datasets. The images show photogrammetric control in the form of cross lines. These markers were measured using a tachymetric method, which allowed them to be used for the external orientation of the images. This enabled the alignment of images from both series and, consequently, the integration of the results into a single coordinate system.

The images obtained from the first phase of excavation were divided into four image groups. It was possible to separate the images depicting the front wall, right wall, back wall, and the excavation. The left wall was not documented in the photographs. The names of the chunks and the number of images in each are presented in Table 6. Relative orientation was performed for each chunk, and Table 2 shows the reprojection errors.

Table 2. Analysis of the Number of Images and Reprojection Errors.

Images group name	Reprojection error [pix]
Front	0.9
Right	1.1
Back	1.0
“Floor” – excavation	0.9

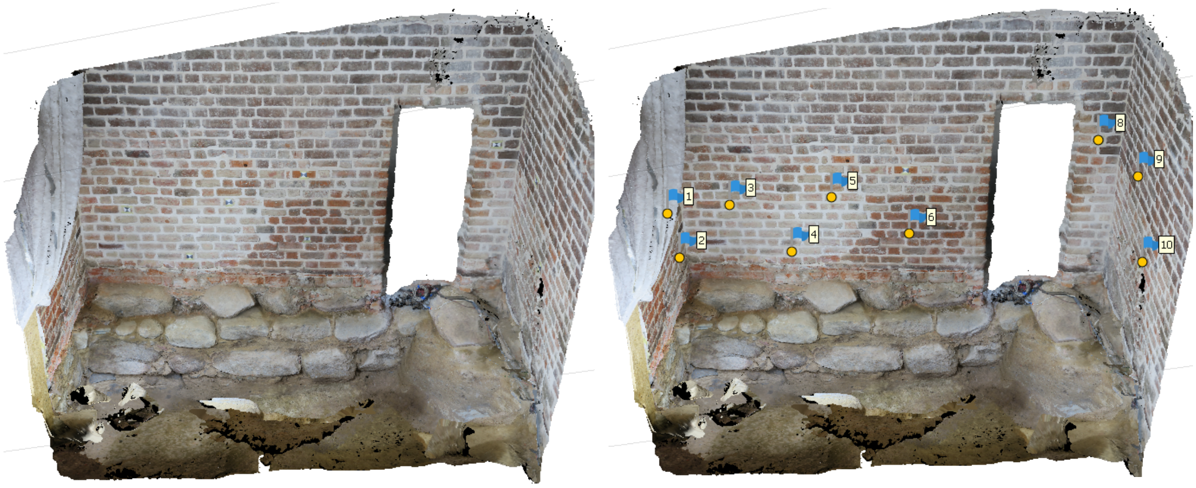
The analysis of the number of images and reprojection errors reveals varying levels of accuracy across the different image groups. The front group, consisting of only 7 images, shows a reprojection error of 0.9 pixels, which is relatively low considering the small number of images. The right group, with 57 images, has a slightly higher reprojection error of 1.1 pixels, indicating a slight decrease in precision as the number of images increases. The back group, with 30 images, shows a reprojection error of 1.0 pixels, which is similar to the right group, suggesting a consistent level of accuracy despite a moderate number of images. The excavation group, containing 81 images, has a reprojection error of 0.9 pixels, similar to the front group despite the larger number of images. This indicates that the increased complexity of the area being photographed did not significantly affect the accuracy of the alignment. Overall, the reprojection errors remain relatively low across all groups, with the right wall showing the highest error, possibly due to the larger number of images involved.

Table 3. Analysis of the images exterior orientation.

Parameter	Value
RMSE reprojection error on control points [pix]	0.8
RMSE reprojection error on control points [pix]	0.4
RMSE on control points [mm]	3.2
RMSE on check points [mm]	3.2

For this group of images, it was possible to conduct the process of external orientation. The results presented in Table 2 indicate that the accuracy of the process achieved 3.2 mm. Assessing the values of both the reprojection errors and the RMSE on control and check points, it can be unequivocally stated that the self-calibration and data adjustment processes were conducted correctly and aligned with the adopted reference system. Furthermore, the absence of outliers confirms the high accuracy of the photo orientation process.

Figure 3 presents the results of the 3D models generated in Epoch 1.



(a) (b)

Figure 3. The textured model of the basement during the first excavation stage: (a) the resulting model, (b) with marked reference points. - Epoch 1.

4.3. Epoch 2

Due to the number and distribution of photos for Epoch 2 (a deep excavation near the right wall), a joint orientation of all photos was conducted. Subsequently, relative orientation (with a reprojection error of 1.0 pixels) and external orientation of the photos were performed, followed by generating a photorealistic model. Figure 4 presents the model with the results of the archaeological work inventory.

(a) (b)

Figure 4. The textured model of the basement during the first excavation stage: (a) front-view, (b) top view. - Epoch 2.

4.4. Epoch 3

The mutual orientation process of terrestrial photos was divided into two stages: the mutual orientation of images groups at different distances for each wall separately and the mutual orientation of photos for all walls combined.

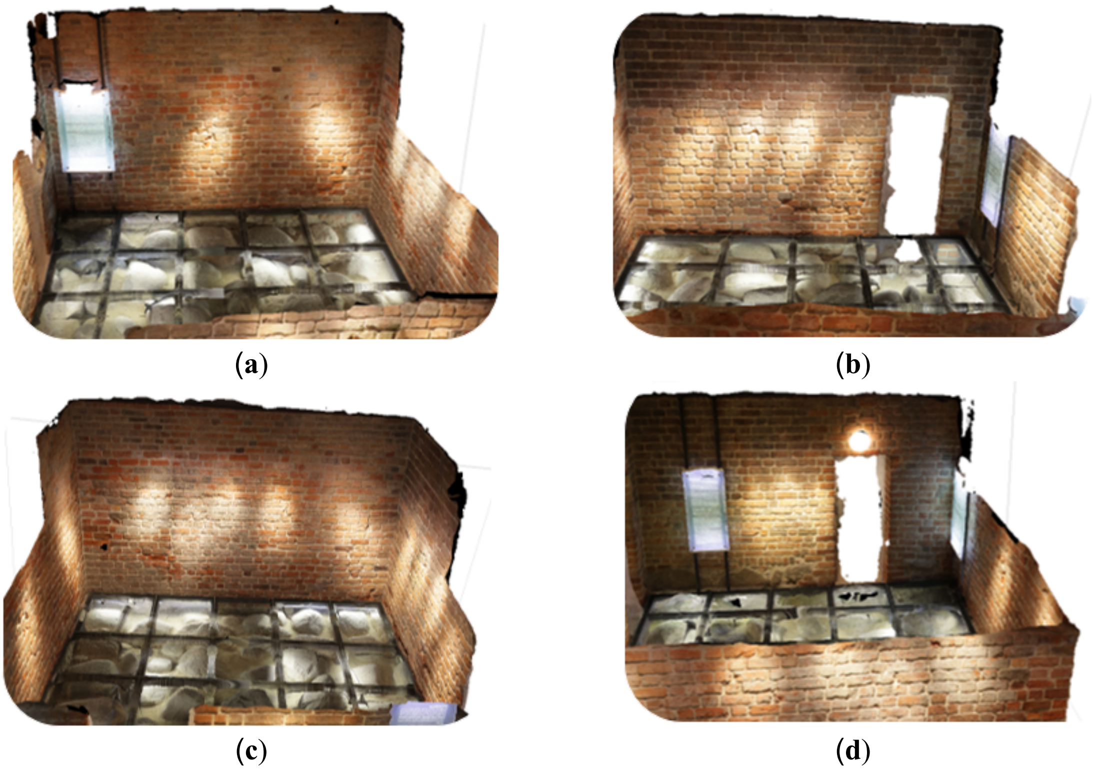
Images taken from long and medium distances aligned accurately for each wall. However, images taken from a close distance aligned fully only for the front wall. For the remaining groups, alignment was successful for only about half of the images. The cause of this issue was poor execution of the close-range images. The software could not align them due to insufficient overlap between the images. The images were taken at a single height, which may have also impacted the final alignment result. In Table 4, the results of images orientation was shown.

Table 4. Analysis of the Number of Images and Reprojection Errors Epoch 3.

Images group name	Reprojection error [pix]
Front	0.5
Right	0.5
Left	0.7
Back	0.6
Floor	0.6

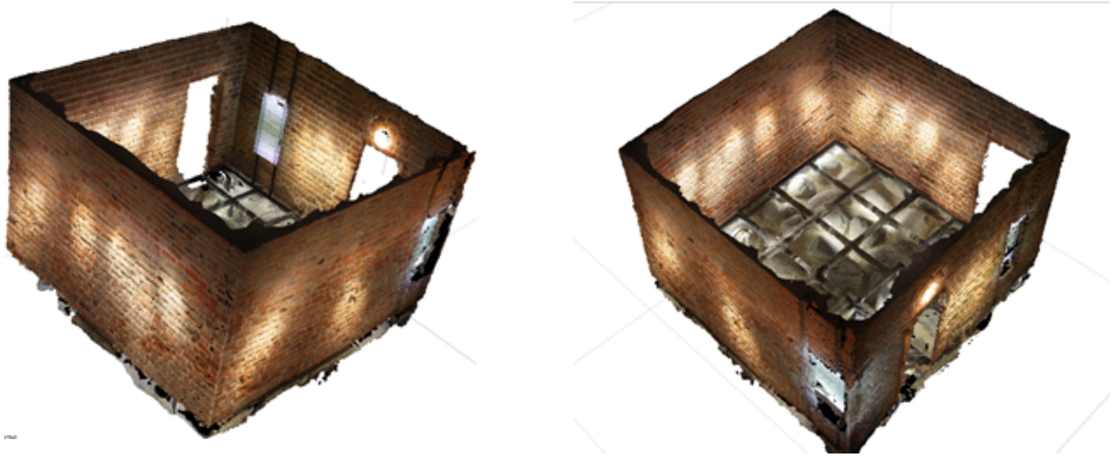
The reprojection errors for the different image groups are generally low and consistent, ranging from 0.5 to 0.7 pixels. The Front and Right groups exhibit the lowest reprojection error of 0.5 pixels, indicating particularly strong alignment in these areas. The Left, Back, and Floor groups show slightly higher errors, between 0.6 and 0.7 pixels, suggesting minor alignment challenges or variability in image capture conditions. Overall, the reprojection errors indicate good alignment and self-calibration quality across all image groups, with only minor discrepancies that could be addressed if higher precision is required.

Similarly to the other Epochs, dense point clouds and 3D models were generated. Figure 5 shows the 3D models generated for Epoch 3.



(a) (b)

(c) (d)



(e)

Figure 5. The photorealistic model: (a) the front wall, (b) the right wall, (c) the left wall, (d) the back wall, (e) the integrated model - Epoch 3.

5. Data integration - summary

The final stage of data processing involved the integration of multi-temporal data. The basement was represented through multiple models, each with dense point clouds generated from images taken during different periods. A multi-temporal integration of photogrammetric data was performed to standardise the reference system for each model. The 3D models of the basement from the first and second phases of excavation were oriented to the external coordinate system using geodetic markers, whose coordinates were known from the photographs. The remaining models were in their own local coordinate systems and were transferred to the external system. Changing the reference system involved identifying common points between the external and local systems models and then performing a joint data transformation based on these common points.

As mentioned earlier, the integration and multi-temporal orientation of the data were performed using the TLS-SfM algorithm. Two types of blob detectors (ASIFT and SURF) and the FAST corner detector were used to detect matching points. Data from all periods were jointly adjusted. Table 5 presents the results of the data integration process.

Table 5. The statistical analysis of the integration process

Detector name	Number of tie points	Registration accuracy – RMSE [mm]		
		X	Y	Z
FAST	0.5	2.2	2.4	2.5
SURF	0.5	2.5	2.8	2.5
ASIFT	0.7	2.1	2.2	2.3

The table presents the tie point detection and registration accuracy results for three different detectors: FAST, SURF, and ASIFT. The ASIFT detector identified the most tie points (0.7), offering the best registration accuracy with RMSE values ranging from 2.1 mm to 2.3 mm across the X, Y, and Z axes. The FAST detector performed slightly less well, with RMSE values around 2.2 mm to 2.5 mm, particularly in the Z-axis. The SURF detector showed the highest errors, especially in the Y-axis (2.8 mm), indicating lower performance in data alignment. Overall, ASIFT proved to be the most effective detector in terms of both the number of tie points and registration accuracy. It should be emphasised, however, that the obtained accuracies are similar, and the results from each approach can be considered equivalent.

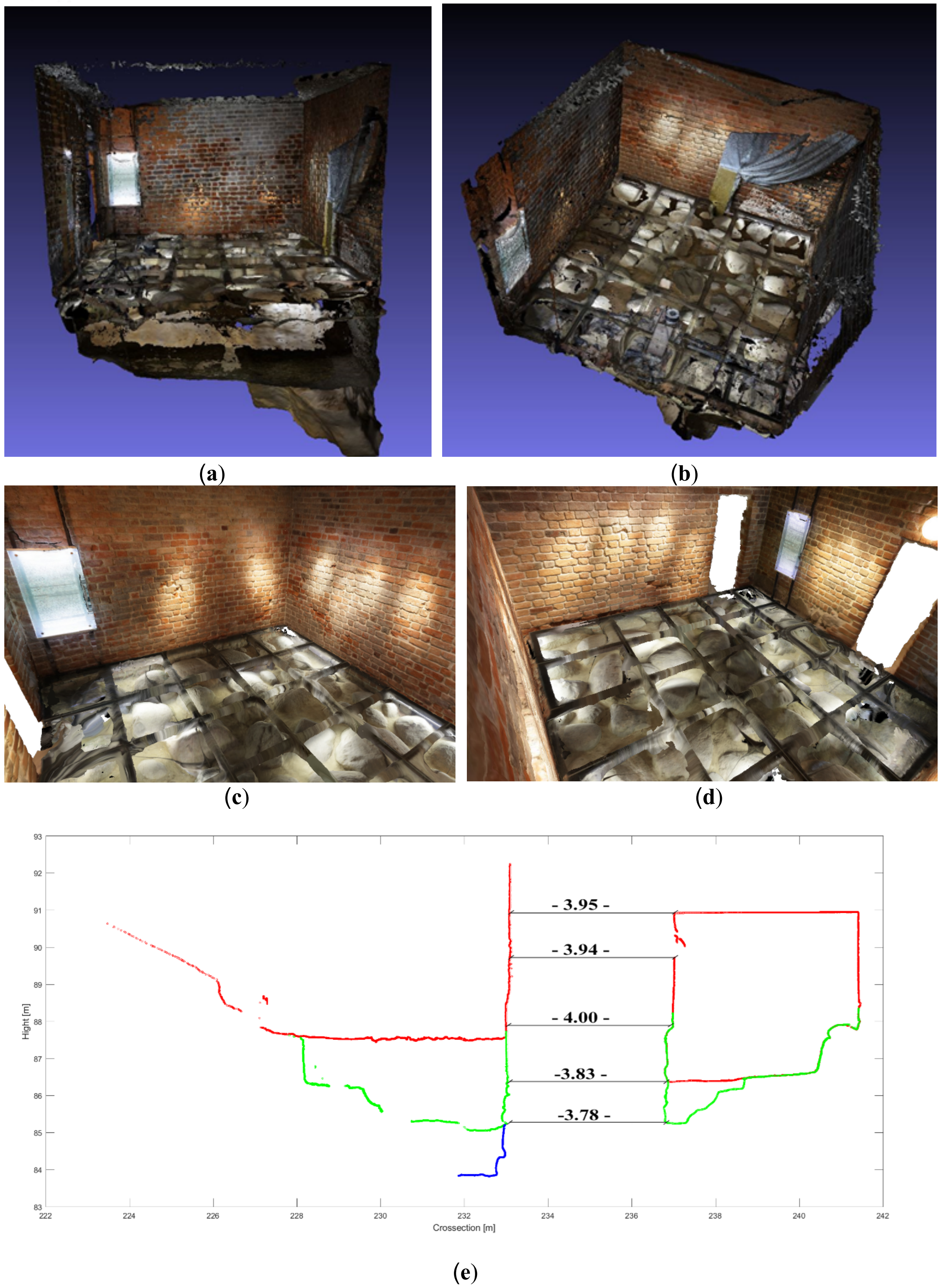

(a) (b) (c) (d) (e)

Figure 6. The examples of the integrated multi-temporal photogrammetric documentation: (a) and (b) the section of the 3D models, (c), (d) the example of 3D models the Justic Tower after archaeological works and (e) the cross sections of the .cross section through the archaeological excavations (Bocheńska *et al.,* 2019).

The research presented in this article aimed to create multi-temporal architectural and archaeological documentation based on ground-based photographs (Fig. 6). For this purpose, both images taken after conservation and archaeological works (depicting the current state of the structure) and archival photographs showing the stages of archaeological work were utilised. This approach allowed for a graphical representation of how the object evolved over time. In summary, the resulting 3D models illustrate different stages of the revitalisation and archaeological work, meet the accuracy requirements for architectural documentation, and can serve not only as a 3D visualisation of the changes in the Prison Hall of the Justice Tower but also as a foundation for planning further conservation and archaeological works. Thanks to the processing of 3D data, it was possible to create documentation in the form of cross-sections, which were used in further architectural and archaeological analyses.

Authors Contributions: J.M.. organised the conceptualisation of the idea and the methodology employed in this paper, A.G. carried out the experimental design. J.M. worked on the data acquisition at the Royal Castle in Warsaw. J.M., M.M. carried out the original writing and draft preparation. J.M., A.G. and M.M. undertook the data analysis, M.M. read and reviewed the manuscript's final version. All authors have read and agreed to the published version of the manuscript.

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