

THE MULTITEMPORAL PHOTOGRAMMETRIC DATA IN ARCHAEOLOGICAL AND ARCHITECTURAL RESEARCH IN THE ROYAL CASTLE IN WARSAW - FIRST RESULTS

J. Markiewicz^{1,*}, D. Zawieska¹, A. Bocheńska³, A. Tobiasz¹, S. Łapiński²

¹ Faculty of Geodesy and Cartography, Division of Photogrammetry, Remote Sensing and Spatial Information Systems, Warsaw University of Technology, Warsaw, Poland - jakub.markiewicz@pw.edu.pl, aleksandratoobiasz777@gmail.com, d.zawieska@gik.pw.edu.pl

² Faculty of Geodesy and Cartography, Division of Engineering Geodesy and Control Surveying System, Warsaw University of Technology, Warsaw, Poland - slawomir.lapinski@pw.edu.pl

³ The Royal Castle in Warsaw, Archaeology Department, Poland - abochenska@zamek-krolewski.pl

Commission II, WG II/8

KEY WORDS: TLS, UAV, SfM, MVS, multitemporal data, multisource data, archaeology, data integration, Royal Castel.

ABSTRACT:

Modern measurement technologies are commonly applied not only to monitor Cultural Heritage objects; they are also applied during archaeological excavation works, when it is important to quickly perform measurements. The paper presents multitemporal integration of different image-based (UAV, close-range digital images) and range-based technologies (Terrestrial Laser Scanning), as well as data acquired in different periods, during archaeological works performed at the Royal Castle in Warsaw, especially for the Justice Court Tower. Measurements were performed in several periods, during deep archaeological excavation works. Due to the limited access to excavations different measurement technologies were applied which allowed to perform measurements within short time. As a results, the DSM (Digital Surface Model), the point cloud and orthoimages were generated. All of the products were stored in the GIS system which will be used for the needs of archaeological and architectural analyses.

1. INTRODUCTION*

The Justice Court Tower, which is the subject of this study, is the oldest brick building of the Royal Castle in Warsaw, the edifice which is almost entirely reconstructed after the destruction it suffered during The Second World War. The number of relics from different historical periods included in the castle buildings is exiguous, these are primarily foundations and basement rooms. This also applies to the Justice Court Tower, which has been dated back to the 14th century. The original cellar located in the basement of the Tower, in the 17th century was adapted to the city prison. From this period come marks carved in bricks, left on the walls of the basement by prisoners. The selection of the object of research and analysis was dictated by conservation reasons. As a result of excessive moisture in the walls, the signs underwent enormous degradation, which in turn, resulted in slow disappearance of the rites. In order to prevent further degradation, it was necessary to undertake quick preservation actions and to create a protection program for decaying carved signs. For this purpose, it was necessary to plan construction works both on the outside of the cellar walls and inside the basement. The necessity of unveiling the outer walls to the level of the tower's foundation gave the opportunity to examine the object in terms both archaeological and architectural. The research program also includes the conservation through documentation. Chosen isolation methods assumed a permanent cover of the historical elements. It was then the only possibility to inventory at least one of the tower's walls in their entirety-from the foundation to the roof. Research and inventory were considerably stretched over time, which was closely related to the construction work schedule and security

considerations. The works were carried out in a deep trench which forced the protection of its the western wall. The piling method was adopted. Due to the applied method, causing significant vibrations, it was decided to make measurements indicating possible displacement of the tower body. Initially, the work was carried out using mechanical equipment, which was used to remove the layers associated with the reconstruction of the Castle. Their thickness reached a depth of 4 m. At the end of this stage, it was possible to take measurements of the exposed, the brick part of western facade of the Justice Court Tower. The next phase was manual exploration up to the foundation level of the Tower. A layer of about 4 m thickness was examined, as a result the foundation plinth was unveiled in its entirety, the height of which was 3 m. At this moment, archaeological research was completed. The next stage was a full inventory using non-invasion photogrammetric methods.

2. METHODOLOGY

For archaeological research, it is important to appropriately record, document, and survey artefacts and sites because an accurate and complete digital documentation is a prerequisite for further analysis and interpretation. For that purpose methods of 3D shapes measurements are applied, basing on active and passive techniques (Arif and Essa, 2017; Grussenmeyer and Yasmine, 2004; Hatzopoulos et al., 2017; Markiewicz et al., 2017; Remondino and El-hakim, 2006) Selection of an appropriate measurement techniques determines the way of data acquisition and processing as well as development of documentation. Both, the active (TLS) and passive (image-based approach) techniques have their advantages and disadvantages (Gonizzi Barsanti et al., 2013).

*Corresponding author

	Photogrammetry (Image-based modelling)	Laser Scanning (Range-based modelling)
Characteristic		
Cost of the instruments	Low	High
Manageability / Portability	Excellent	Sufficient
Time of data Acquisition	Quite short	Generally long
Time of data acquisition	Quite short	Generally long
Distance's dependence	Independent	Dependent
Dimension's dependence	Independent	Dependent
Material's dependence	Almost independent	Dependent
Light's dependence	Dependent	Almost/totally Independent
Geometry's dependence	Quite dependent	Independent
Scale	Absent	Implicit (1:1)
Open-source software	Many	A few

Table 1. Synthesis of photogrammetry and laser scanning techniques and characteristics (Gonizzi Barsanti et al., 2013)

Nowadays, research works concerning the Cultural Heritage and archaeology utilise integration of many techniques, including aerial and UAV (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 photogrammetric (Gonizzi Barsanti et al., 2013; Grussenmeyer and Yasmine, 2004; Hatzopoulos et al., 2017; Remondino and El-hakim, 2006). For the purposes of discussed analyses the authors used UAV, terrestrial and low-cost photographs and TLS data were used as reference data. Additionally, they all were processed in one reference system, basing on geodetic measurements.

3. DATA COLLECTION

The division of the inventory process of the tower walls was necessary due to the phased character of the renovation works and limited, overtime, accessibility of individual parts of the walls. The documentation of the tower's ground part was the easiest to do. This stage of work was limited only by atmospheric conditions and it was made in the first place. However, a significant part of the historical facade is located under the surface of the ground, covered by layers formed over several centuries. It is the part that is adverse affected by the environment in which it lays. The result was a serious moisture in the walls which caused poor conservation conditions created in the interior located in the basement. It was necessary to completely uncover the outer western facade and secure the brick part from further degradation by applying vertical insulation. The revealed part of the walls largely consists of original fourteenth-century elements (Kąsinowski, 1960) and unveiling it gave the opportunity to examine its structure. According the schedule of renovation works the next step was to secure the brick part before uncovering the stone foundation.

The project assumed putting on the walls ever a insulating layers permanently covering the historical facade. It was important to take an inventory of the exposed wall before it was insulated, which had to be done before undertaking further research. The lowest parties, consisted of the stone foundation of the Tower, were uncovered in a much narrower trench than the other elements, which also forced a change of the documentation method. The phased of the actions was forced by the schedule of conservation works and the possibility of adapting the documentation method to the existing conditions during the research is a great convenience and the integrated data can be used not only to create a visualization and virtual reconstruction of the examined object, but above all are the subject of many useful analysis.

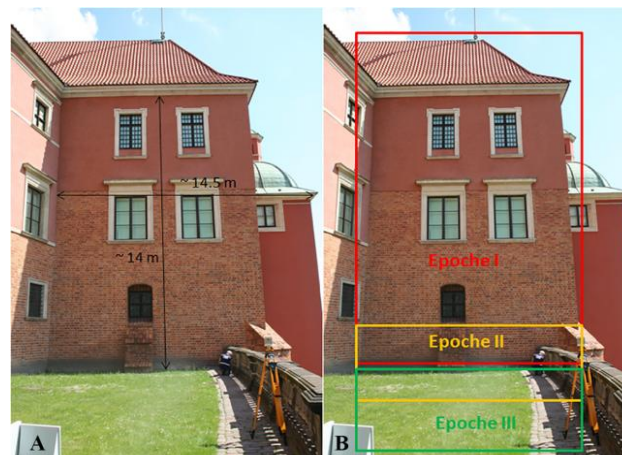


Figure 1. The tower with marked heights

3.1. The subject of the study

The detailed subject of analyses discussed in this paper was the monumental Justice Court Tower located at the edge of an escarpment. Both, its location and dimensions require particular attention during the positioning of the measuring stations. On the one hand, the high tower ($H=14$ m) is inaccessible for direct measurements, and the partial projection of its shape is possible, on the other (Fig. 1A).

3.2. Performed measurement

For that purpose, in order to inventory a multitemporal archaeological excavation it was decided to apply different photogrammetric techniques, i.e. the close-range s - Z+F 5006h, UAV DJI Phantom 3 Pro, close-range images - Canon 5D Mark II, the low-cost, Olympus C-5050Z sensor and the mobile phone camera included in Samsung Galaxy J3 (Tab. 2). Measurements were divided into three stages (Fig. 1B). Works were performed by two teams, i.e. a team of surveyors and photogrammetrists from the Warsaw University of Technology and a team of trained archaeologists from the Royal Castle.

One, uniform and common reference system for all types of data is an important element which allows to integrate data acquired from the UAV, TLS and cameras. Besides, considering the multitemporal inventory, this system must be stable in time. The reference system consists of two elements: the coordinate system and stabilised points of the control. The local system was assumed as the X,Y,Z coordinate system. Coordinates of the control points are the 1-order control for referencing all types of data; the appropriate construction for the control allows to analyse its stability in time.

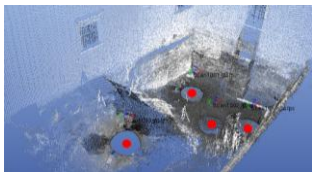
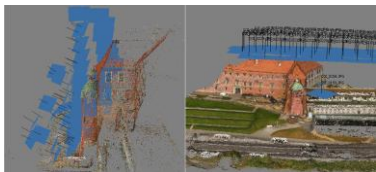
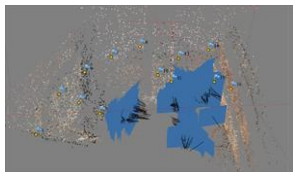
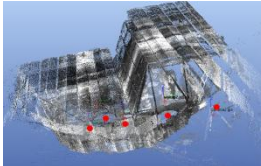
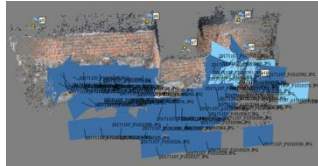
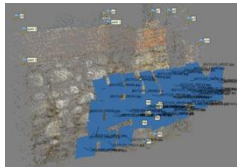
Sensor	TLS	UAV (the low-cost DJI Phantom 3 Pro)	Close-range images
Epoch I	<ul style="list-style-type: none"> - 4 scans - Z+F 5006h - resolution of 6 mm/10m - performed from the inside and from the outside of the excavation 	<ul style="list-style-type: none"> - vertical images (65) with the approx.GSD value of 2 cm - the altitude of approx. 54 m - automatically flight - velocity of 2.7 m/s - oblique images (144) with the approx. GSD value of 5cm - the altitude of approx. 26 m - the manual flight 	<ul style="list-style-type: none"> - full-frame camera Canon 5D Mark II - no. of images - 227
			
Epoch II	<ul style="list-style-type: none"> - 5 scans - Z+F 5006h scanner - resolution of 6 mm/10m - from the inside and from the outside of the excavation 	No data	<ul style="list-style-type: none"> - Olympus C-5050Z camera - no. of images - 70
			
Epoch III	No data	No data	<ul style="list-style-type: none"> - Smartphone Samsung Galaxy J3 - no. of images - 62
			

Table. 2. The overview of used equipment with defined measurements parameters

Measurements were performed using the Leica 1201+ total station which allows to measure angles with 1" and the reflector distance measurement with 1 mm +1.5 ppm. The positioning accuracy for the 1-order control equals to 2 mm. The geodetic control was measured in two epochs (I and II). Displacements of reference points were not noticed, after the analyses and comparison of positions of points in both measurement epochs. The accuracy of determination of points of the photogrammetric control, not worse than 3 mm was obtained.

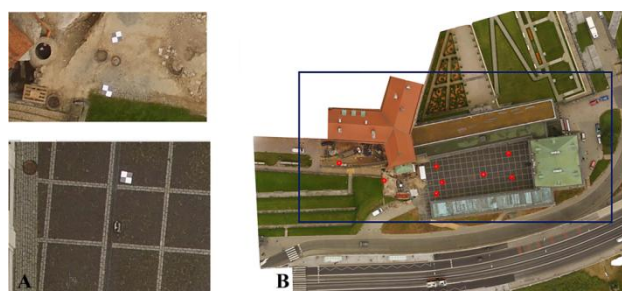


Figure 2. The ground control points on tested area. A) The example of the used target, B) The sketch of distributed ground

control and check points. Red colour - points, the blue rectangle - tested area. The photogrammetric control check points were also defined (Fig. 2A) around the analysed excavation and its closest surroundings (Fig. 2B).

3.3. Data processing

In order to generate the final photogrammetric documentation it was necessary to process and integrate data in the State Geodetic Coordinate System 2000. Agisoft PhotoScan software was used to orientate and process images; to process TLS data Z+F LaserControl and LupoScan software were used. Table 3 presents parameters used for image processing. Depending on the data, the following data processing schemes were applied:

1. TLS data processing: (a) relative orientation of point clouds, (b) exterior orientation of point clouds, (c) data filtration aiming at elimination of noises (filtration of intensity, influence of the scanning angles and elimination of mixed-edges effects), (d) quality control of analysed surfaces and comparison from particular scanner positions - selection of fragments in order to generate the high resolution digital surface model for the object, (e) generation of intensity orthoimages.

Epoch I - UAV		Epoch I - Images		Epoch II	Epoch III		
Alignment							
Accuracy	High	Accuracy	High	Accuracy	High	Accuracy	High
Pair preselection	Yes	Pair preselection	No	Pair preselection	Generic preselection	Pair preselection	Disable
No. of tie points	35476	No. of tie points	828684	No. of tie points	88639	No. of tie points	53254
Dense Point Cloud							
Point Quality	High	Point Quality	High	Point Quality	High	Point Quality	High
No. of point	21933197	No. of point	26967136	No. of point	3556871	No. of point	2594241

Table 3. The main parameters used in image processing

2. Processing of images: (a) orientation of images with the use of the SfM (Structure-from-Motion) method, (b) generation of the high density point cloud with the use of the MVS (Multi-View-Stereo) method, (c) quality control basing on TLS data, (d) generation of high density 3D models and RGB orthoimages.

The results of data registration was shown in Table 4. The process of terrestrial laser scanning data orientation was performed in two stages: the relative and the absolute orientation was performed in order to register data in the assumed reference system. Marks dedicated for the Z+F 5006h scanner were used as reference points.

At the first stage images acquired from the low-cost UAV were processed using the Agisoft PhotoScan software. Due to destination of images, nadir and oblique images were separately processed. Approximate elements of the exterior orientation, acquired during the flight, were used as initial data. For nadir and oblique images the calibrated focal value, coordinates of the principal point, radial distortion parameters (k_1 , k_2 and k_3) and tangential distortion parameters (p_1 and p_2) were determined in the self-calibration process. Additionally, it was decided to determine parameters related to the rolling shutter effect for nadir images.

As a reference data, the ground control (6) and check (4) points from the geodetic measurements were used.

Close-range image processing was divided into three epochs. The following parameters were determined for each case in the self-calibration process: the calibrated focal value, coordinates

of the principal point, parameters of the radial distortion (k_1 , k_2 and k_3) and parameters of the tangential distortion (p_1 and p_2). UAV images

The obtained results prove the correctness of the performed data orientation process. Lower accuracies obtained for oblique images resulted from projection of control points under bigger angles what considerably affected the accuracy and uniformity of identification of the mark centre.

Close-range images

The obtained results prove the high orientation accuracy of close-range images in particular epochs. However, it will be necessary to perform the reciprocal orientation of all data in the process of integration of data from different sources, in order to eliminate errors generated during the orientation of images from different measurement epochs. Comparing the results obtained from Olympus, the old digital camera (epoch II) with data from the Samsung Smartphone (epoch III) it should be noticed that higher accuracies are obtained for the Olympus camera. Despite the lower matrix resolution results are considerably better since the camera is equipped with the lens of the better geometric properties.

4. RESULT OF DATA INTEGRATION - THE COMPLEX INVENTORY

In order to perform comprehensive assessment of conditions of the monumental object, the Justice Court Tower, it was necessary to integrate multitemporal data acquired by different sensors, used in many epochs. In order to evaluate the accuracy of performed orientation of photographs, TLS data were applied as reference data.

Epoch	Sensor	No. of		RMSE reprojection error [px]	Control points - RMSE [mm]			Check points - RMSE [mm]		
		Control points	Check points		X	Y	Z	X	Y	Z
I	TLS	8	6	-	3.3	3.3	3.2	2.8	3.4	2.9
	UAV (nadir)	6	4	0.7	1.3	2.2	1.1	1.0	2.6	1.0
	UAV (oblique)	6	4	0.9	4.4	0.9	2.8	1.5	0.2	2.5
	Canon Mark 5D II	8	6	0.4	1.3	2.2	1.1	1.0	2.6	1.0
II	TLS	7	4	-	2.8	4.2	1.5	3.5	2.0	6.2
	Olympus C-5050Z	4	2	0.5	1.4	1.4	1.4	2.6	1.6	1.4
III	Smartphone Samsung Galaxy J3	4	2	0.9	2.7	2.0	3.3	1.8	2.4	6.1

Table 4. The results of data registration

The possibility to place geodetic control points was limited by the nature of the researched object and by performed archaeological works. This also caused that numbers of points used for particular epochs were different. However, analyses of point clouds were performed in order to assess the accuracy of particular stages of image processing.

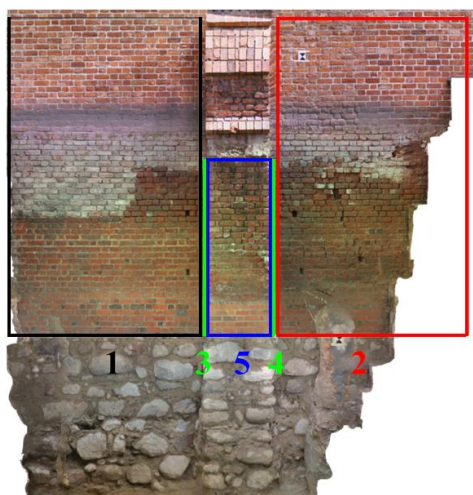


Figure 3. Marked tested areas on the orthoimages from all of the epochs

4.1. Analyses of differences between TLS point clouds and photographs in particular epochs

At the initial stage, differences between point clouds from images and TLS point were evaluated for particular epochs. For the needs of comprehensive evaluation of integrated point clouds analyses were performed for 5 control sites, where archaeologists will perform detailed archaeological and architectural analyses (Fig. 3). The objective of such detailed analysis was to test the accuracy of the shape projection which may be achieved for particular sensors and to check whether it meets the requirements of such analyses.

Summarising the results obtained for particular sensors (Appendix 1, Tab. 5) diversification of results may be noticed, which may be considered negligible for archaeologists in the case of large excavations. This leads to the general conclusion that both, a full frame camera, as well as a Smartphone camera may be used. However, the appropriate photograph processing must be considered.

Epoch	Deviations between point clouds $< 2.5 \sigma$		
	X [m]	Y[m]	Z[m]
I	± 0.00195	± 0.0021	± 0.0017
II	± 0.0020	± 0.0036	± 0.0018
III	± 0.0074	± 0.0049	± 0.0025

Table 5. The mean values of deviations smaller than 2.5σ

4.2. Investigations of twist of point clouds from photographs from different epochs

Due to the monumental nature of the researched object and measurements performed in different epochs of archaeological excavations, it was decided to perform more detailed analyses of investigated fragments of surfaces of objects. It should be noticed that the object foundation (detected during excavation works) was an original construction and remaining parts of the object were reconstructed. Therefore it was decided to check mutual relations of planes registered in fragments of point clouds from different epochs. Due to relatively low mutual overlap (about 10%) of point cloud and applied protections and shelters of excavations, such analysis allows to check the mutual orientation of investigated point clouds.

In order to determine the parallelism of planes it was necessary to determine the scalar product of normal vectors of planes. When planes are parallel the coefficient equals to 1. As a result of performed analyses, the coefficient equalled to 0.9996. Therefore the value of twist of planes and the maximum differences were determined (Tab. 6, 7). All of the epochs were analysed in this way.

Epoch	Average angle of planes twisting $[\circ]$	Average max distance between planes [m]
I	0.1541	0.0027
II	0.1544	0.0039
III	0.3844	0.0062

Table 6. The average angle of plane twisting with the average max distance between planes for three epochs.

Such analyses are useful for performing highly detailed analyses and researching historical surfaces of monuments; determined differences are negligible when the general approach is considered.

Test field	Data source (point cloud)	Plane normal vector			Parallelism coefficient	Plane twisting angle $[\circ]$	Difference of angles $[\circ]$	Max distances between planes [m]
		A	B	C				
1	TLS	0.97555	0.21971	0.0051888	0.999986	89.7027	-0.2528	-0.0044
	Images	0.97561	0.21929	0.0096019		89.4498		
2	TLS	0.97392	0.22687	0.00096596	0.999980	90.0553	0.2205	0.0038
	Images	0.97466	0.22363	0.0048154		90.2759		
3	TLS	0.21678	-0.97621	-0.0034953	0.999980	90.2002	-0.0540	-0.0009
	Images	0.21071	-0.97755	-0.0025524		90.1462		
4	TLS	-0.21829	0.97588	0.0041668	1.000001	89.7612	-0.0587	-0.0010
	Images	-0.21689	0.97618	0.0051927		89.7024		
5	TLS	0.96697	0.25483	0.0060365	0.999968	89.6541	-0.1845	-0.0032
	Images	0.96898	-0.24698	0.0092569		89.4696		

Table 7. The example parameters used for plane parallelism analysis (Epoch I)

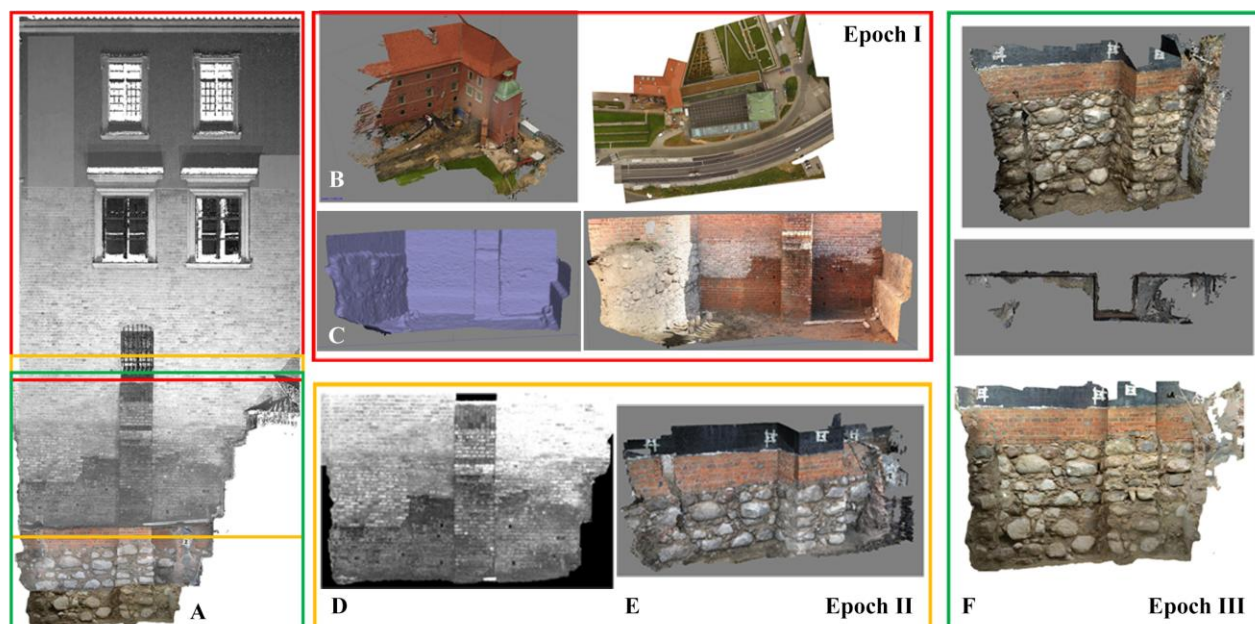


Figure 4. Results of integration of multitemporal data: A) the combined multitemporal image, B) the 3D model 3D and true-orthophoto from the DJI Phantom 3 Pro (Epoch I), C) the 3D model and the RGB orthoimage for the upper part of the excavation (Epoch I), D) the intensity orthoimage from TLS Z+F 5006h, and E) the 3D model from images of the central part of the excavation (Epoch II), F) the 3D model and the RGB orthoimage for the bottom part of the excavation (Epoch III)

4.3. Final products and data integration

The following results were obtained for particular measurement epochs as a result of data processing and integration: All data and resulting products will be recorded in the designed GIS system for archaeological excavations of the Royal Castle in Warsaw. Additionally, it be amended with multitemporal images (Fig. 4A).

5. CONCLUSIONS

During the archaeological excavations works of the Justice Court Tower many sensors were used in different periods. Precise TLS data (considered as reference data), as well as digital images of different resolution, acquired from different ceilings were used. All data were oriented in one reference system. The accuracy analysis of particular data, acquired by different sensors, proved that - for such analyses - it is possible to acquired metric products even when low-cost sensors are applied. The possibility to achieve such results is determined by the appropriate data processing approach.

Precision measurement is a top priority. By examining the obtained image, one may attempt to stratify chronologically the fragment of the wall. One of the methods used for this purpose is metric brick analysis.

the bricks, depending on the period and the terrain, have changed, and the three-order system (length, thickness and height of the brick) allows to identify the time of brick

Arif, R., Essa, K., 2017. Evolving Techniques of Documentation of a World Heritage Site in Lahore. ISPRS - Int. Arch. Photogramm. Remote Sens. Spat. Inf. Sci. XLII-2/W5, 33–40. <https://doi.org/10.5194/isprs-archives-XLII-2-W5-33-2017>

Del Pozo, S., Rodríguez-González, P., Sánchez-Aparicio, L.J., Muñoz-Nieto, A., Hernández-López, D., Felipe-García, B., González-Aguilera, D., 2017. Multispectral Imaging in Cultural

formation. With the adoption of such a test method, the precision of measurements and the possibility of ordering the results in the form of a statistical statement is extremely important. By minimizing the error of measuring the size of bricks, we increase the probability of correctness of the obtained results.

The measurement should be strictly carried out using geodetic methods, e.g. on the basis of fixed geodesic constants - horizontal and vertical. This allows you to capture all wall deformations and brick work distortions, which can carry information for both the architectural, historian and, above all, for the conservation project (deformations, dilatations) and structural analysis. Inventory should also be all fragments of plaster and remains of coloured layers.

The entire documentation created in this way will become the basis for creating a three-dimensional database based on GIS, which will make managing a huge amount of information and documentation much easier

The virtual 3D models created on this occasion may also serve popularizing purposes. The creation of a virtual reconstruction of the building and the accessibility of invisible parts of the walls may serve exhibition purposes and enrich the Museum's educational offer.

REFERENCES

- Heritage Conservation. ISPRS - Int. Arch. Photogramm. Remote Sens. Spat. Inf. Sci. XLII-2/W5, 155–162. <https://doi.org/10.5194/isprs-archives-XLII-2-W5-155-2017>
- Drap, P., Durand, A., Nedir, M., Seinturier, J., Papini, O., Gabrielli, R., Peloso, D., Kadobayashi, R., Gaillard, G., Chapman, P., Viant, W., Vannini, G., Nucciotti, M., 2007. Photogrammetry and Archaeological Knowledge: Toward a 3D Information System Dedicated to Medieval Archaeology: A

Case Study of Shawback Castle in Jordan. Int. Arch. Photogramm. Remote Sens. Spat. Inf. Sci.

Gonizzi Barsanti, S., Remondino, F., Visintini, D., 2013. 3D Surveying And Modeling Of Archaeological Sites - Some Critical Issues; ISPRS Ann. Photogramm. Remote Sens. Spat. Inf. Sci. II-5/W1, 145–150. <https://doi.org/10.5194/isprsannals-II-5-W1-145-2013>

Grussenmeyer, P., Yasmine, J., 2004. Photogrammetry for the Preparation of Archaeological Excavation. A 3D Restitution According to Modern and Archive Images of Beaufort Castle landscape (Lebanon). Int. Arch. Photogramm. Remote Sens. 809–814.

Hatzopoulos, J.N., Stefanakis, D., Georgopoulos, A., Tapinaki, S., Pantelis, V., Liritzis, I., 2017. Use of various surveying technologies to 3D digital mapping and modelling of cultural heritage structures for maintenance and restoration purposes: The Tholos in Delphi, Greece. Mediterr. Archaeol. Archaeom. 17, 311–336. <https://doi.org/10.5281/zenodo.1048937>
Koistinen, K., 2004. Multitemporal archaeological imagery to model the progress of excavation 1006–1011.

Kąsinowski 1960 – A. Kąsinowski, Warszawa – Zamek Królewski. Zespół piwnic gotyckich skrzydła wschodniego. Badania architektoniczne, Szczecin 1960, typescript in the Archive of the Royal Castle in Warsaw

Markiewicz, J., Zawieska, D., Podlasiak, P., 2017. Comparing multi-source photogrammetric data during the examination of verticality in a Monumental tower. Int. Arch. Photogramm. Remote Sens. Spat. Inf. Sci. - ISPRS Arch. 42, 475–480. <https://doi.org/10.5194/isprs-archives-XLII-2-W3-475-2017>

Murtiyoso, A., Koehl, M., Grussenmeyer, P., Freville, T., 2017. Acquisition And Processing Protocols For Uav Images: 3d Modeling Of Historical Buildings Using Photogrammetry, in: ISPRS Annals of the Photogrammetry, Remote Sensing and Spatial Information Sciences. pp. 163–170. <https://doi.org/10.5194/isprs-annals-IV-2-W2-163-2017>

Nocerino, E., Menna, F., Remondino, F., 2012. Multi-Temporal Analysis of Landscapes and Urban Areas. Xxii Isprs Congr. Tech. Comm. Iv 39-B4, 85–90. <https://doi.org/10.5194/isprsarchives-XXXIX-B4-85-2012>

Remondino, F., El-hakim, S., 2006. Image-based 3D modelling: A review. Photogramm. Rec. <https://doi.org/10.1111/j.1477-9730.2006.00383.x>

Sauerbier, M., Eisenbeiss, H., 2010. Uavs for the Documentation of Archaeological Excavations. Proc. Isprs Comm. V Mid-Term Symp. Close Range Image Meas. Tech. 38, 526–531.

APPENDIX A The statistic of point cloud deviations obtained from TLS and images

Epoch I							
No. of test field	Mean				< 2.5		
	X [m]	Y[m]	Z[m]	L[m]	X [m]	Y[m]	Z[m]
1	-0.0007	-0.0002	0.0000	0.0016	±0.0010	±0.00012	±0.0013
2	-0.0011	-0.0002	0.0000	0.0020	-0.0031 0.0008	±0.0015	±0.0015
3	0.0000	0.0001	0.0001	0.0013	±0.0019	±0.0029	±0.0018
4	0	0.0004	0.0001	0.0019	±0.0028	±0.0033	±0.0023
5	0.0009	0.0002	0.0000	0.0020	±0.0021	±0.0026	±0.0016
Epoch II							
1	-0.0019	-0.0004	-0.0001	0.0032	-0.0064 0.0021	±0.0016	±0.0018
2	-0.0008	-0.0002	0.0000	0.0021	0.0017	±0.0014	±0.0015
3	-0.0004	0.0019	0.0000	0.0042	0.0027	0.0076	0.0017
4	-0.0007	0.0033	0.0000	0.0042	0.0025	0.0059	0.0029
5	-0.0002	0.0000	0.0001	0.0007	0.0011	0.0014	0.0013
Epoch III							
1	0.0030	0.0007	-0.0002	0.0043	-0.0016 0.0079	0.0039	0.0022
2	0.0046	0.0008	-0.0008	0.0122	0.0171	0.0093	0.0056
3	0.00004	-0.0015	0.0000	0.0056	0.0029	-0.0068 0.0037	0.0014
4	-0.0015	0.0032	0.0002	0.0040	-0.0044 0.0008	-0.0025 0.0067	0.0014
5	-0.0007	-0.0002	0.0001	0.0020	0.0022	0.0014	0.0017