THE COMBINATION OF THE IMAGE AND RANGE-BASED 3D ACQUISITION IN ARCHAEOLOGICAL AND ARCHITECTURAL RESEARCH IN THE ROYAL CASTLE IN WARSAW

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ABSTRACT:

The paper presents archaeological and architectural research in the Royal Castle in Warsaw where a combination of image- and range-based 3D acquisition was applied. The area examined included excavations situated inside the Tower and near its outer western wall. The work was carried out at various periods and in different weather conditions. As part of the measurements, laser scanning was performed (with a Z+F 5006h scanner) and a series of close-range images were taken. It was important to integrate the data acquired to create a comprehensive documentation of archaeological excavations. When data was acquired from TLS together with photogrammetric data (in different measurement periods), the points' displacements were controlled and analysed. The process of orienting and processing the terrestrial images included photographs taken during the inventory of the tower (Canon 5D Mark II) and photographs provided by the Castle's employees (Canon PowerShot G5 X). Agisoft PhotoScan software was used to orient and process the terrestrial images, and LupoScan for the TLS data. In order to integrate the TLS data and the clouds of points from the photographs from the various stages, they were processed into a raster form; our own software (based on the OpenCV library and the Structure-from-Motion method) and LupoScan software were used to interconnect the multi-temporal and multi-sensor data sets. As a result of processing photographs and TLS data, point clouds in an external reference system were obtained. This data was then used to study the thickness of the walls of the Justice Court Tower, to analyse the course of the retaining wall, and to generate the orthoimages necessary for chronological analysis.

1. INTRODUCTION

During archaeological research it is extremely important to meticulously document the levels which are unearthed. Failing to do this means losing a fundamental source of knowledge, as it is impossible to recreate such data. During excavations, particular layers connected with the object analysed may be irretrievably lost without any further possibility of recreating the primary structure, which may carry data on the historical monument's chronology among others. In so-called urban archaeology, architectural relics have a special place; they are one of the more important sources which testify to the tangible culture of past decades. Conducting accurate inventory of the existing walls in conjunction with the analysis of adjacent layers is thus extremely important. This option is possible thanks to contemporary methods of documentation, both in the area of registration and the further analyses of the data obtained.

The data presented is the result of cooperation between representatives of the humanities and science. The aim of the project was to prepare complete digital documentation of the archaeological excavations carried out within the Royal Castle in Warsaw. The excavations took place near the Justice Court Tower, also known as the Great Tower in the Middle Ages, and which was most probably raised in the third quarter of the 14th century. It is the oldest existing brick edifice which is part of the castle complex. The excavation work carried out in its vicinity and inside was connected with a conservation program whose objective was to save the unique house marks located on the inside walls of the Prison Cellar, the lowest usable floor of the Tower. However, it should be mentioned that the Royal Castle in Warsaw has almost entirely been reconstructed. The number of relics coming from various historical periods is negligible; the same is true of our knowledge of how the settlement in Warsaw functioned during its most remote periods. Only the foundations and castle cellars, including the Prison Cellar, survived the damage done during the Second World War. The location of the work carried out is extremely important not only because the layers unearthed are part of the original substance, but also, and maybe most of all, because they relate to the beginnings of Warsaw as a city.

The contemporary shape of the southern foot of the Castle, known as the Southern Terrace, is the result of large-scale early modern and contemporary investments and related concepts for landscaping. Especially in the post-war period, the region underwent a complete transformation. Despite substantial interference, during the current works it was possible to reach those layers which had not been damaged, including the layer connected with the raising of the tower, that is, the excavation batch prepared for the foundations.

2. STATE OF THE ART

Many research projects require accurate and complete digital documentation of cultural heritage objects and sites for the sake of analysis and interpretation, and in some cases also to aid in

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their restoration. This is particularly important in archaeological research, and so it should be noted that proper registration and documentation of artefacts and sites allow for proper further analysis and interpretation. For that purpose, the image-based (passive methods, i.e. close-range photogrammetry) as well as range-based (active methods, i.e. Terrestrial Laser Scanning - TLS) techniques for 3D shape reconstruction are applied (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 El-hakim, 2006). The active (range-based modelling) and passive (image-based approach) techniques have their advantages and disadvantages (Gonizzi Barsanti et al., 2013). The main advantages of the image-based approach are: (1) the price of the instrument – cameras cost much less than terrestrial laser scanners, (2) smaller devices in comparison to TLS are more convenient in places which are hard to reach, such as deep excavations, (3) shorter measurement times, in comparison with TLS, (4) independence from the size of the objects examined and the shooting distance – the only limitation is the resultant density of the clouds of points and the GSD of the photographs. On the other hand, there are also disadvantages to the image-based approach: (1) complete automation is impossible, (2) occlusions on poor and un-textured areas and repetitive structures, (3) dependence on the lighting conditions. The advantages of the TLS (range-based) method include: (1) high accuracy, (2) a large number of points forming a quasi-continuous surface, (3) a high level of automation of measurements, (4) the possibility to record the laser-beam reflectance intensity, which might be used to investigate the properties of the object analysed and (5) the possibility to measure untextured areas, which is the principal advantage. The main disadvantages of the range-based TLS are: (1) the laser beam propagates with distance, which can result in uncertainty regarding the location of the determined point, (2) a problem regarding the intensity of the laser beam reflection (the point is located incorrectly, or not enough fragments of the object being analysed are measured, (3) the mixed-edge problem which causes incorrect measurements of the edges.

Nowadays, because all these methods have their benefits and drawbacks, it is common to integrate both close-range photogrammetry and TLS when carrying out research work concerning cultural heritage and archaeology (e.g. 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; Koistinen, 2004; Markiewicz et al., 2017; Murtiyoso et al., 2017; Nocerino et al., 2012; Remondino and El-hakim, 2006; Sauerbier and Eisenbeiss, 2010). For the purpose of multi-temporal archaeological excavations and research, close-range photogrammetry and TLS data were used.

3. PERFORMED EXPERIMENT

To carry out the geodetic and photogrammetric measurements, two measurement methods were used: the close-range terrestrial scanner Z+F 5006h; and close-range images on the Canon 5D Mark II with a low-cost Olympus C-5050Z. The research was divided into five stages (Figure 1). The work was carried out by two teams, a team of surveyors and photogrammetrists from the Warsaw University of Technology, and a team of trained archaeologists from the Royal Castle in Warsaw.

3.1. Surveying

The researched area included excavations situated inside the Tower and near its outer western wall (Figure 2) Carrying out deep excavations made it possible to uncover the foundations of the Tower to the level of the foundations and register its primary construction

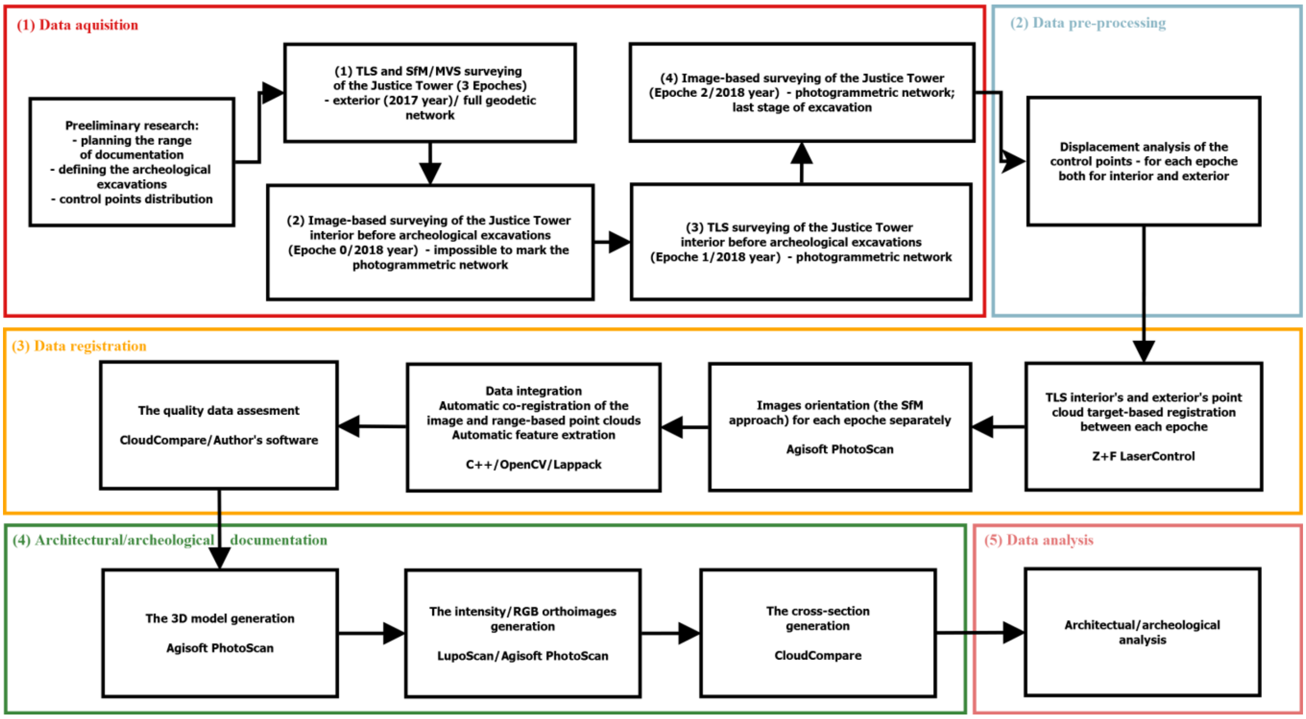

Figure 1. The block diagram of the performed experiment.

Figure 2. A) A section of a true-orthophotomap with the excavation area marked; B) example of the exterior excavation; C) the analysed interior

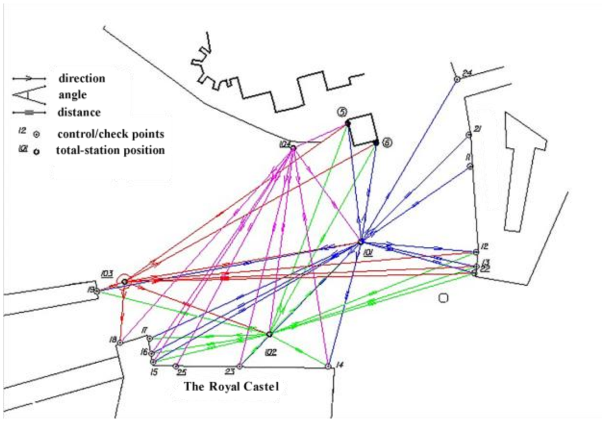

Figure 3. Example of a geodetic network (first-order) used for data registration

Due to the historic character of the building, the registration was done with the non-invasive technique of terrestrial laser scanning, mainly using the Z+F 5006h and close-range photogrammetry (Markiewicz et al., 2018). The work was carried out at various periods and in different weather conditions. It was important to integrate the data acquired in order to create a comprehensive profile of the area studied. For that purpose, a geodetic first-order control network was designed and placed (Figure 3).

Measurements were performed using the Leica 1201+ total station which allows measurement of angles of 1" and reflector distance measurement of 1 mm +1.5 ppm. Appendix 1 presents the aligned coordinates of the geodetic first-order control points together with the accuracy measurements to determine the position of the points in the adopted local coordinate system X, Y, H. Because of construction work (deep excavations), it was necessary to monitoring (measurement of displacements) the geodetic control points in time. The geodetic first-order control points were the primary and unified reference system for establishing a photogrammetric second-order network, which was an important element of the relative orientation of different types of data.

Moreover, archaeological and inventory work was carried out inside the Justice Court Tower. In order to set the coordinates of the points located there, the coordinates of the positions located between the outer part of the building and the inside of the Tower were transformed in the adopted datum connected with the outer vicinity of the Royal Castle. The positions created a hanging traverse. A three-tripod method consisting in placing three stations, one instrument and two prisms, was used as a measuring method. Measurements were taken between the stands, but their relative location was not changed. This allowed for more precise measurement results and helped minimise the possibility of errors. The coordinates from the outer reference system were transferred to the inside of the tower where a photogrammetric network was set up. The X and Y coordinates of the photogrammetric network were calculated with the polar method, whereas the H coordinate was calculated with the trigonometric levelling method. The horizontal, vertical angles and oblique distances were observed in two series in order to eliminate the possibility of so-called gross errors in observations. The observations taken for the calculations were averaged from two measurements. This data was used for the TLS data (Figure 4) and image registration.

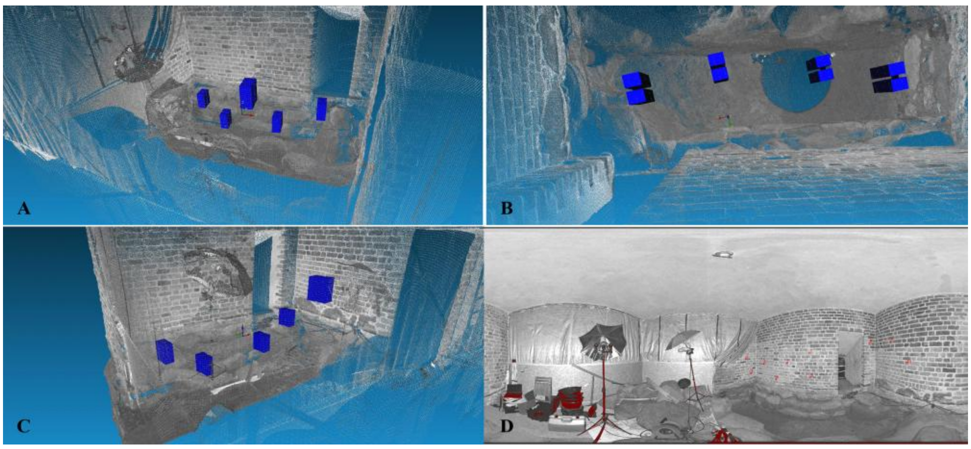

Figure 4. The example locations of scanner stations (A-C) with the control points marked in the spherical image (D).

Images		TLS					
No. of images	380	Station	No. of control points	No. of checkpoints	RMSE on control points [mm]	RMSE on check points [mm]
RMSE reprojection error on control points	0.8	1	4	5	1.3	1.0
RMSE reprojection error on control points	0.4	2	4	4	1.4	1.9
RMSE on control points	3.2 mm	3	3	2	1.5	1.8
RMSE on check points	3.2 mm	4	4	4	1.3	0.9
		5	4	3	1.4	1.4

Table 1. The results of the processing of TLS data and photographs with the Structure-from-Motion method

3.2. Image and range-base measurements

The process of orientation and processing the terrestrial images included photographs taken during the inventory of the boulders stabilizing the construction of the tower (set I - 275 photographs taken with Canon 5D Mark II) and photographs provided by the castle’s employees (set II - 380 photographs taken with Canon PowerShot G5 X, Figure 5). The Agisoft PhotoScan software was used to orient and process the terrestrial images. Table 1 presents the results of the alignment of the TLS data and the photographs.

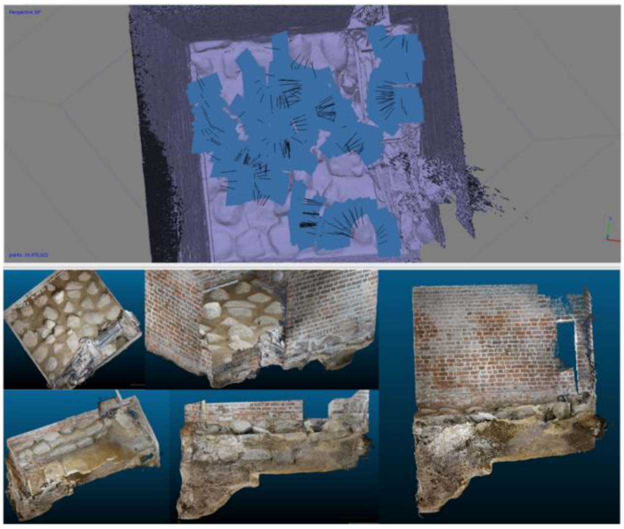

Figure 5. The example of images location and generated point clouds

During the first stage, the orientation of the first set of photographs was carried out on the basis of the photogrammetric network. This allowed them to be incorporated into the outer reference system and to generate 3D models. These oriented and fitted photographs were used as references for the second set of photographs where check and control points were not placed. The process of align the images from the second set consisted in detecting the common points in both sets and common data processing. In order to integrate the clouds of points from the photographs taken at various stages, they were processed into a raster form; we used our own software based on the OpenCV library and the Structure-from-Motion method. The detailed description of the way the cloud of points was processed can be found in Markiewicz and Zawieska (2019), among others. Figure 6 shows an example of detecting binding points on two clouds of points which have been converted into a raster form.

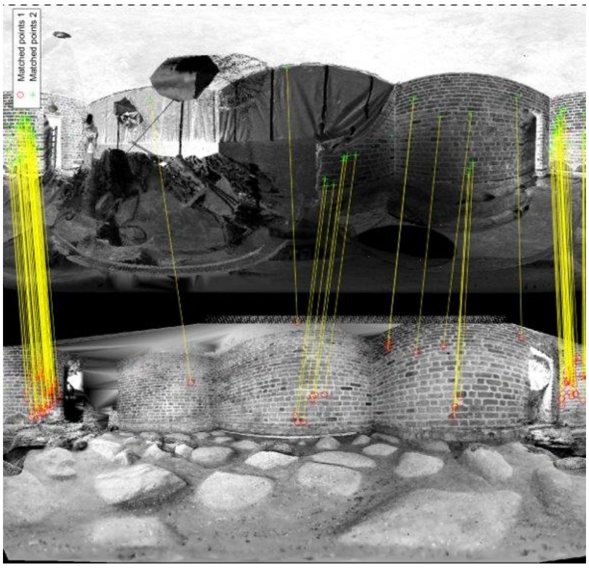

Figure 6. The example of images location and generated point clouds

Because it was not possible to assess the accuracy of the process of orienting the marked check and control points of the photographs from the second set, it was decided to analyse the distances between clouds of points on the selected test sections.

The analysis of the histograms of deviations between clouds of points shows that they roughly adopt a Gaussian distribution (normal distribution) and didnot exceed 5 mm, which proves that the orientation of terrestrial photographs from the first stage was carried out correctly (Figure 7).

4. RESULT AND ANALYSIS

As a result of processing and orienting photographs and TLS data, clouds of points in an external coordinate system were obtained. This data was used to study the thickness of the walls of the Justice Court Tower (Figure 9), to analyse the course of the retaining wall, and to generate the orthoimages necessary for chronological analysis (Figure 8). The information obtained allowed us to verify the landform where the Tower had been raised and gave the opportunity to accurately determine the thickness of the walls.

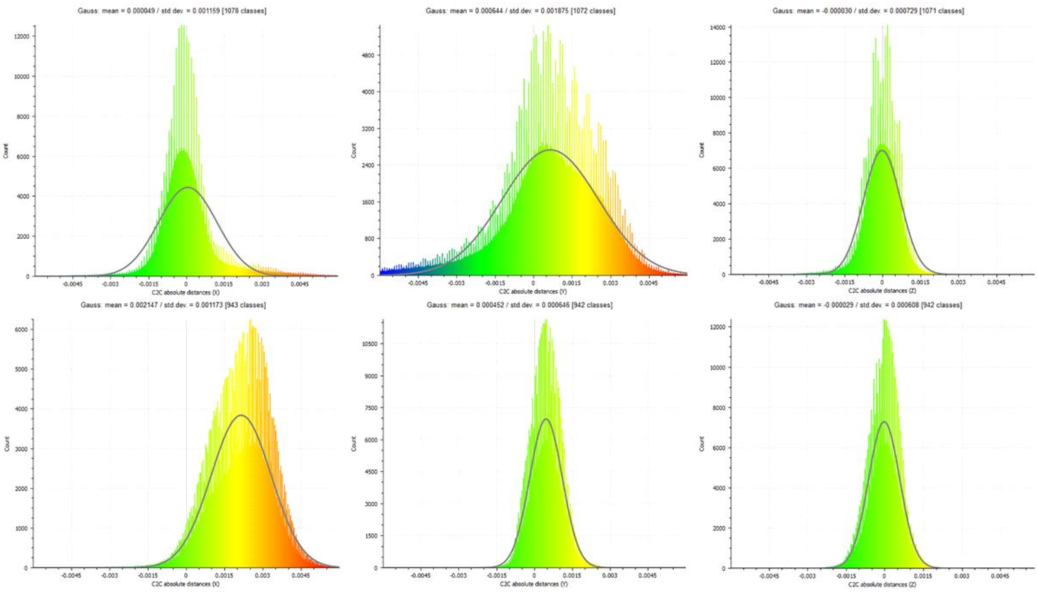

Figure 7. Histograms of deviations on test sections between clouds of points created during stages I and II

The full profile of the station (Figure 9) allowed us to trace the sequence of the construction process, starting from preparatory phases to the full project implementation. A deep excavation for the foundations of the western wall of the Tower can be seen in the attached cross-section. Its upper parts were offset by contemporary investments; the original level of the fill layers is marked by the blue arrow. The eastern side of wall A reveals a stepped construction of wall N’s foundations which were built on the slope of the hill constituting the base of the building. Consequently, the stone base of the eastern wall was reduced to 1m in height. The difference in the levels of the foundation of opposite walls equals approximately 2.5 metres.

The work in this place, on the western side of the Justice Court Tower, was important for one more reason. It provided the opportunity to verify the theory which had been devised after the discoveries in the adjacent courtyard of the Tin-Roofed Palace, where excavations took place in 2004-2007. These resulted in unearthing the relics of two defensive systems, a wooden and earthen rampart and its parallel stone and brick wall. Both constructions were erected on a northeast-southwest axis. Based on the stratigraphic observation and analyses of the position of both structures relative to each other, Michał Sekuła drew the conclusion that both the wall and the rampart were not in situ, and their location at the moment of their discovery was the result of a geological catastrophe which had taken place in the past. The landslide occurred from the area adjacent to the current Justice Court Tower. According to Sekuła, in the primary configuration, the tower and the wooden and earthen rampart co-existed (Sekuła, 2011, 2007), and thus created a uniform defensive system.

However, from the preliminary analysis of the latest research it does not appear that the wooden and earthen rampart moved. It seems that during the catastrophe which undoubtedly took place, only a large section of the brick and stone wall was damaged as it slid down and crushed the wooden defences (Figure 10). However, before the wall was built the Tower had been a free-standing construction which did not have any wooden strengthening. During the excavations on the western side of the Tower, no traces of existence of any wooden constructions connected with the Tower were found. Only the above-mentioned large construction excavation prepared for the foundations was recorded.

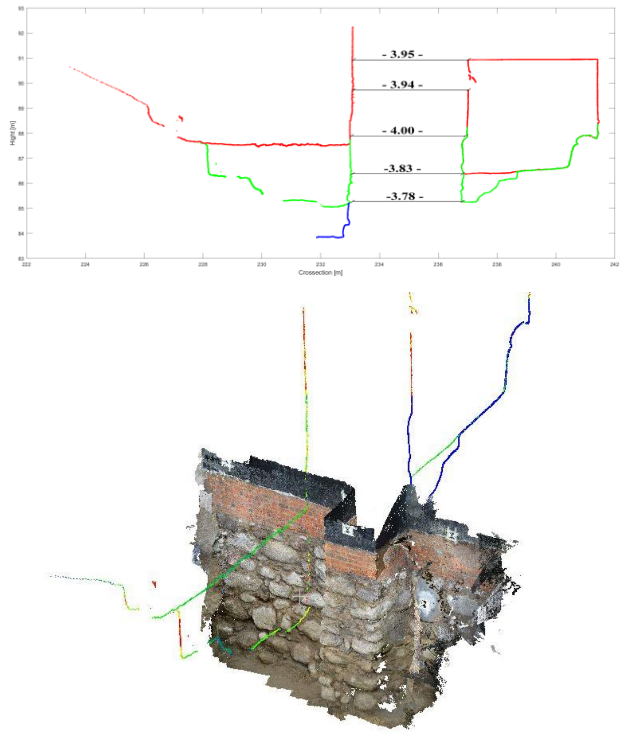

Figure 8. Example cross-section with marked measurements

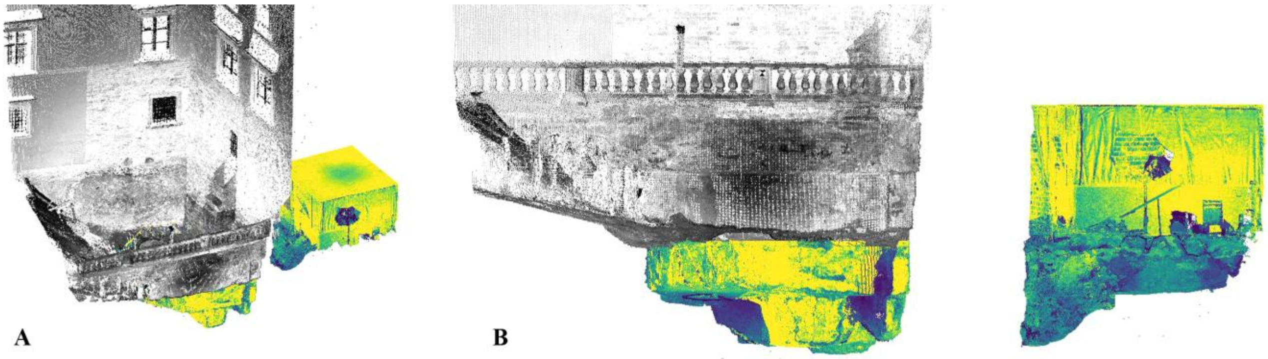

Figure 9. Example clouds of points used in analysing the thickness and the state of preservation of the Justice Court Tower’s walls

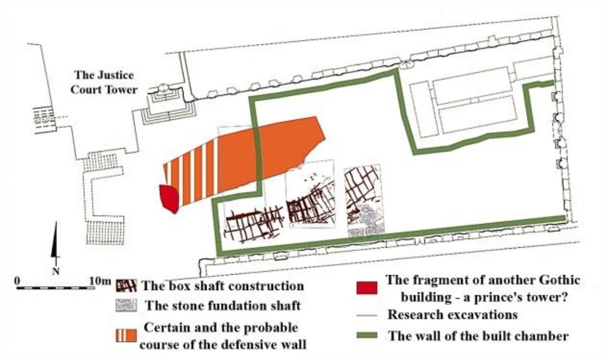

Figure 10. Mutual relation between the uncovered relics of the two defensive systems unearthed at the courtyard of the Tin-Roofed Palace. Devised by M. Sekuła

The shape of the settlement’s headland is not the only subject of dispute among scientists. The matrix of the Tower is also controversial. Initially the construction was dated to the end of the 13th century (Skórewicz, 1924), then to the first half of the 14th century (Kąsinowski, 1962). The latest research dates it to the third quarter of the 14th century. The chronology of the Tower was determined on the basis of analyses of a brick thread and the dimensions of the bricks used to build the preserved parts of the walls. The numerous transformations that the body of the castle underwent over the centuries effectively blurred the traces of the oldest constructions. During the latest excavations, an attempt at chronological stratification of the dense wall was made. For that purpose, orthoimages of the reflection intensity of the laser beam on the outer part of the wall and the wall of the Prison cellar were used.

Bricks from different historical periods were characterised by different reflection intensity. It is visible in Example A of Figure 11. Dark grey which clearly cuts off marks the boundaries of the original walls.

In order to confirm the chronological uniformity of a selected wall section, an innovative method of thermoluminescence dating consisting on determining the time of creation of objects heated during the production process, usage or a random event to a temperature of at least 350 °C was used. Four bricks with the same degree of reflection were chosen for the analysis. The approximate dates acquired confirmed that they came from the same period.

(red) sample nr 1 1360
(green) sample nr 2 1357
(blue) sample nr 3 1348
(yellow) sample nr 4 1363

Table 2. Results of the thermoluminescence dating of brick samples from the western outer wall of the Justice Court Tower.

5. CONCLUSION

During the archaeological excavations in the Justice Court Tower many sensors were used at different periods. Also, precise TLS data (considered as reference data) and digital images of different resolutions acquired from various ceilings and periods were used. All the data was oriented into one reference system. The registration processes were based on the marked control points, but the automatic feature-based registration method was also used.

The accuracy analysis of the particular data acquired by different sensors proved that it is possible to acquire metric products for the purpose of such analyses, even when low-cost sensors are used. Such results can be obtained with the appropriate approach to data processing.

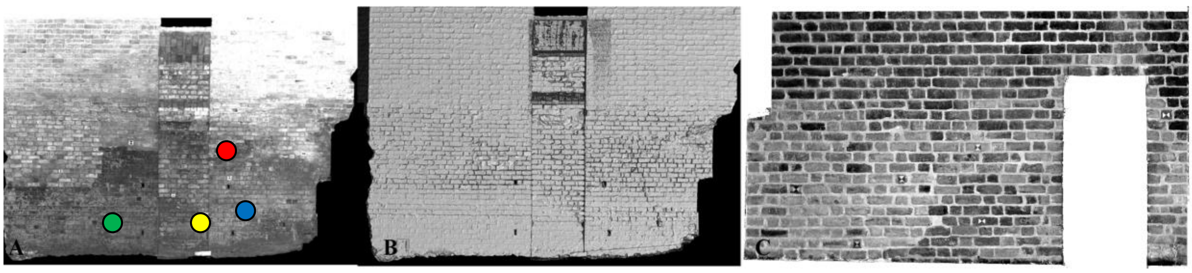

Figure 11. Example A) orthoimage in the intensity of outer wall of the Justice Court Tower with dating marked (Table 3), B) Shaded digital object model, c) orthoimage of the intensity of one of the walls in the Prison cellar.

The whole documentation allowed an extended architectural and archeological analysis to be performed.

A comprehensive image of the object examined was obtained, thanks to adjusting the method of documentation to the current weather conditions during the work in progress, together with the possibility to integrate the data. The full profile of the station allowed us to trace the sequence of the construction process, starting from preparatory phases to the full project implementation. The detailed analysis of the levels documented made it possible to verify the theories adopted, as well as the results of previous research. The controversial post-war reconstruction of the Prison Cellar may serve as an example.

Analysis of the bricks from the Prison Cellar's northern wall showed that it had been decided to completely rebuild the wall, despite the original wall being preserved to at least three-quarters of its height. During the excavations, the wall was entirely dismantled and then built again with the original material. The gaps were filled with bricks from other periods. Unfortunately, this fact had not been recorded, and until the latest excavations it had been assumed that the wall had remained intact to the present day. Rebuilding was also confirmed by the analysis of the location of the bricks' engraved characters, which had been inventoried before the reconstruction. Having compared the photographs, it turned out that some of them had been displaced. Rebuilding using non-original bricks was also confirmed by the analysis of the reflection intensity.

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APPENDIX 1. The aligned coordinates and the position determination accuracies (X, Y, Z) of the first-order control points.

Aligned coordinates XYZ						
No	X [m]	Y [m]	H [m]	mX [m]	mY [m]	mH [m]
8	45.8531	148.1919	99.3468	0.0005	0.0005	0.0008
11	61.215	100.3655	99.6349	0.0007	0.0009	0.0008
14	135.3446	160.9539	95.4759	0.0004	0.0003	0.0006
15	130.9312	232.5959	95.2355	0.0008	0.0006	0.0007
16	130.6286	232.6624	94.7653	0.0008	0.0006	0.0007
17	123.6288	234.1956	95.0493	0.0008	0.0006	0.0007
18	118.3146	244.5031	87.4102	0.0011	0.0004	0.0007
19	103.5141	253.0822	87.3963	0.0009	0.0005	0.0007
21	40.8374	101.4414	101.1483	0.0008	0.0009	0.0009
22	100.0257	100.0104	100.0001	0.0004	0.0004	0.0006
23	132.9302	204.1054	95.5136	0.0008	0.0005	0.0007
24	-12.4138	106.5388	100.0806	0.0007	0.0002	0.0009
25	131.8381	222.0548	95.6405	0.0008	0.0005	0.0007
101	82.1488	150.0136	95.8888	0.0004	0.0003	0.0005
102	45.7316	175.7519	92.2480	0.0005	0.0005	0.0007
103	100.2609	248.1243	84.9912	0.0009	0.0004	0.0007
104	107.9068	190.3853	90.0508	0.0006	0.0003	0.0006