Advances in Science and Technology
Research Journal

Advances in Science and Technology Research Journal 2023, 17(6), 345–357
https://doi.org/10.12913/22998624/174063
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Received: 2023.07.07
Accepted: 2023.10.12
Published: 2023.11.22

The Case Study of Using Photogrammetric Systems and Laser Scanning for Three-Dimensional Modeling of Cultural Heritage Sites

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ABSTRACT

Advancements in digitizing technologies in recent years have enabled the creation of precise three-dimensional models using specialized equipment such as terrestrial laser scanners. Unfortunately, working with a device placed on the ground surface makes it impossible to directly measure roof structures, building vertices and hard-to-reach areas. However, unmanned aerial vehicles equipped with high-resolution cameras and a precise control system that allows maneuvers in the aforementioned places have a chance in this field. This article presents the complete process of digital 3D modeling of the town hall building in Zamość, using a combination of photogrammetry and laser scanning, along with geodetic measurement techniques. The study covers the planning stage, the field stage, and ends with accuracy analyses. Finally, the potential applications of the aforementioned object are discussed. The research identified several challenges during the project, including the need for meticulous planning to ensure optimal data acquisition, dealing with limitations of equipment mobility, and addressing data quality issues such as image blurriness and exposure variations. However, through careful calibration, data filtering, and quality assessment, these challenges were successfully mitigated. The study demonstrated the potential of advanced geodetic techniques in accurately digitizing complex architectural structures with rich historical significance. The detailed 3D model of the Zamość town hall serves as a valuable resource for further research, preservation efforts, and heritage documentation.

Keywords: drone photogrammetry, terrestrial laser scanning, three-dimensional (3D) modeling, heritage documentation.

INTRODUCTION

In recent years, there has been a growing interest in three-dimensional (3D) digital modeling of various structures [1, 2, 3], which is reflected in the increasing demand from both public and private recipients [3, 4]. Objects ranging from miniature sculptures to massive buildings and entire complexes undergo digitizing procedures [3, 5, 6]. Building modeling was mainly done with laser scanners, which can accurately record the shape and details of architectural structures. In addition, digital spatial models are indispensable in the growing BIM (Building Information Modeling) technology. [7, 8, 9]. This process was limited by very high costs, due to the price of terrestrial and aerial laser scanners (TLS and ALS), as well as photogrammetric equipment in the form of metric digital cameras and measurement drones. Currently, all this equipment has been reduced to the role of a single, expensive device. (e.g drone fitted with lidar sensor or terrestrial laser scanner that offers generating 3D mesh automatically). A different possible solution comes in the form of a hybrid data acquisition method, utilizing laser scanners that have been on the market for some time, amateur drones, as well as consumer-grade photographic cameras, offering a dynamic and versatile approach to 3D modeling [10, 11]. This study delves into the application of hybrid data acquisition methods for the digital modeling of the Zamość town hall, a prominent architectural landmark enlisted in the UNESCO World Heritage List. The research is aimed at investigating the potential of integrating ground-based laser scanner, drone and digital camera measurements, and consequently evaluating the resulting measurement accuracies, attempting to address the limitations of these methods, analyzing the acquisition time of the results, the effectiveness in capturing complex architectural details and enhancing heritage preservation efforts. The process entails planning, fieldwork, and data processing protocols to generate a 3D model. Subsequently, an extensive accuracy analysis is conducted to evaluate the reliability and effectiveness of the resulting digital representation. Remarkably, the absence of any documented cases employing this methodology for the specific subject in the literature contributes a distinctive aspect to our research. The scarcity of prior examples highlights the importance of exploring new avenues and expanding the horizons of three-dimensional modeling in cultural heritage sites.

The process of digitizing a 3D object should begin with an understanding of the mechanisms that stand behind it. The first technology used in the project, digital photogrammetry, has gained prominence since the 1980s with the advancement of computer processing power, enabling the handling of multiple digital images simultaneously. At the same time, CCD matrice cameras enabled image recording in raster form [12]. The evaluation of light and color information for individual pixels (RGB space) resulted in a matrix-form image with rows and columns. Photogrammetric measurement involves raster observations within a specified area, often arranged in a grid to ensure precise overlapping of images [12]. In the past, camera coordinates and rotation angles were measured using devices like photo-theodolites [13]. Nowadays, mutual image and photopoint orientation enable precise calculation of camera positions and angles [12, 14]. The images are presented in central projection, formed by intersecting the projection plane with projecting rays [12]. Then, the images are processed on a digital photogrammetric station, i.e., a computer equipped with the appropriate hardware and software for processing the measured data. The tasks performed on the station include: mutual, internal, and absolute orientation, automatic or semi-automatic aerotriangulation, measuring data for a digital terrain model (DTM), creating point clouds and 3D mesh The second technology used, laser scanning, is relatively young, with the first terrestrial laser scanner introduced in 1998 [15]. Unlike photogrammetry, it employs laser or LIDAR (Light Detection and Ranging) devices, working similarly to radar but using infrared instead of microwave waves [10]. The first technique that TLS uses for measuring distance is the time-of-flight (TOF) method, using the speed of light to measure distances to objects (Figure 1).

When a pulse of light is emitted from a pulsed laser diode, an internal clock starts. The light bounces off the object and returns to the scanner system, hitting a photodetector that stops the clock, providing accurate distance measurements. The more recent, phase-shift method in lidar employs a continuous laser source with modulated power at a constant frequency. Photodetectors analyze the returning signal's power, enabling the formation of a sine curve that helps determine precise distances to objects. Unfortunately, it was unable to utilize this technology as the scanner used in this project supported only TOF measurements. LIDAR systems can calculate target

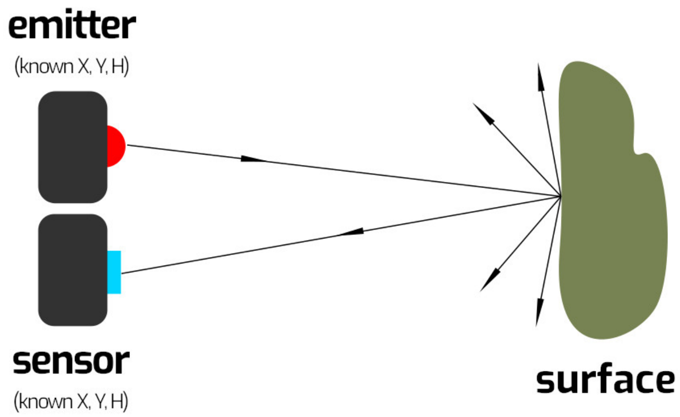


Fig. 1. Principle of operation of the laser scanner (own sources)

distances with high accuracy, for capturing coordinates (X, Y, H) [15], lidar scanners are equipped with highly precise sensors that record the vertical and horizontal rotation angles of the instrument during data acquisition. This information enables the calculation of precise 3D coordinates for each point within the scanned area. Lidar systems can capture millions of points per second, resulting in dense point clouds that represent the shape and characteristics of the scanned object or terrain. By analyzing these point clouds, information such as surface geometry, vegetation distribution, or building details can be obtained. The result is a digital terrain model. Due to the number of measured points in the given time, the model is characterized by a high density of data and accuracy of up to millimeters, surpassing photogrammetric methods both in terms of measurement time and quality of processed results [16]. The disadvantage of those devices is mostly their low mobility, making them not usable for measuring hard-to-reach areas. Therefore, to obtain optimal results, it is suggested to use both techniques combined, which can complement each other [16]. Modern photogrammetry and remote sensing programs support laser scanning [17, 18] and allow the creation of an object model from observations in both raster and discrete, numerical form [3, 4, 17].

PLANNING STAGE

The object selected for measurements was the town hall building in the city of Zamość, inscribed in 1992 on the UNESCO World Heritage List. It is the main building in the old town of Zamość and is located on the northern side of the Great Market Square. It has a 52-meter clock tower and wide, fan-shaped stairs. The building consists of the main town hall with an annex and was chosen due to its rich history and significance for the city [16]. In addition, it has been popular among research teams for many years. For example, a digital processing of the front elevation of the building was already carried out in 1998 [6]. The rich decorations and the resulting high degree of complexity of the structure were also important factors, which allowed for comparing the accuracy of the measuring equipment used. In order to carry out the digitizing process of the building, it was necessary to plan the survey works, select the appropriate equipment for the task, and obtain all necessary permits through administrative procedures. Currently, there are devices available on the market capable of creating precise 3D models (e.g., Rock R3Pro /RIEGL miniVUX paired with DJI M300 drone platform). However, they remain financially out of reach for many companies. To achieve a building model with accuracy comparable to traditional laser scanning but at lower costs, the equipment shown in the tables below was assembled (Table 1).

The scope of work to be carried out with the help of the equipment had to be established first. Initially, twelve measurement stations for a terrestrial laser scanner, as well as twenty photopoints (PL2000 rectangular coordinate system - zone eight, PL-EVRF-2007 height system [20]) had to be established using a total station. Then, the terrestrial laser scanner had to be placed at each of the 12 control points and the building had to be measured at the specified angle [17]. The last stage of field work was to produce visualizations of the town hall using a drone (roof, upper elevations, tower) and a photographic camera (element directly above the ground, lower part of the stairs) [6, 21, 14]. The equipment that was planned to be used included a Topcon ES-105 total station, Topcon GLS-2000 terrestrial laser scanner, DJI Mavic 2 Pro drone, and Canon 6D digital camera with Tokina 16-28mm lens. Following the completion of fieldwork, the processing tasks were performed using Adobe Lightroom, Topcon ScanMaster and Agisoft Metashape software on a dedicated workstation. Due to the use of a drone in the measurements, it was necessary to check if the flight area was not in an airspace restricted from aviation and obtain permission from the Zamość City Office to allow the UAV flight over the town hall. The order of work is shown in Figure 2.

FIELD STAGE

The date the work was carried out was chosen as March 31 2023 due to favorable weather conditions. The work began with a site reconnaissance and selection of the scanner stations that would provide the best coverage of the study area. The stations were marked on the ground, and then proceeded with measurements which were intended to determine their coordinates with an accuracy that meets the geodetic requirements of the Minister of Development from August 18, 2020 [22]. The chosen method of measurement

Table 1. Equipment with parameters utilized during measurements

Equipment	Device model	Parameters and settings
Total station	Topcon ES-105	- <1" angle accuracy
		- 500m non-prism range (3mm + 2ppm accuracy)
		- 4000m prism range
Terrestrial Laser Scanner	Topcon GLS-2000	- distance accuracy: 3.5mm at 1m-150m
		- max range: 500m
		- angle accuracy: 6 arc-seconds
Unmanned Aerial Vehicle	DJI Mavic 2 Pro	- GNSS positioning accuracy: ±1.5m
		- camera: L1D-20c
		- resolution: 5472 x 3078
		- focal length: 10.26mm
		- pixel size: 2.53 x 2.53 μm
Non-metric digital camera	Canon EOS 6D	- resolution: 5472 x 3648
		- focal length: 24mm
		- pixel size: 6.58 x 6.58 μm
Workstation	Lenovo Legion 5	- RAM: 32GB DDR4
		- CPU: AMD Ryzen 7
		- GPU: Nvidia RTX3060Ti 6GB vRAM

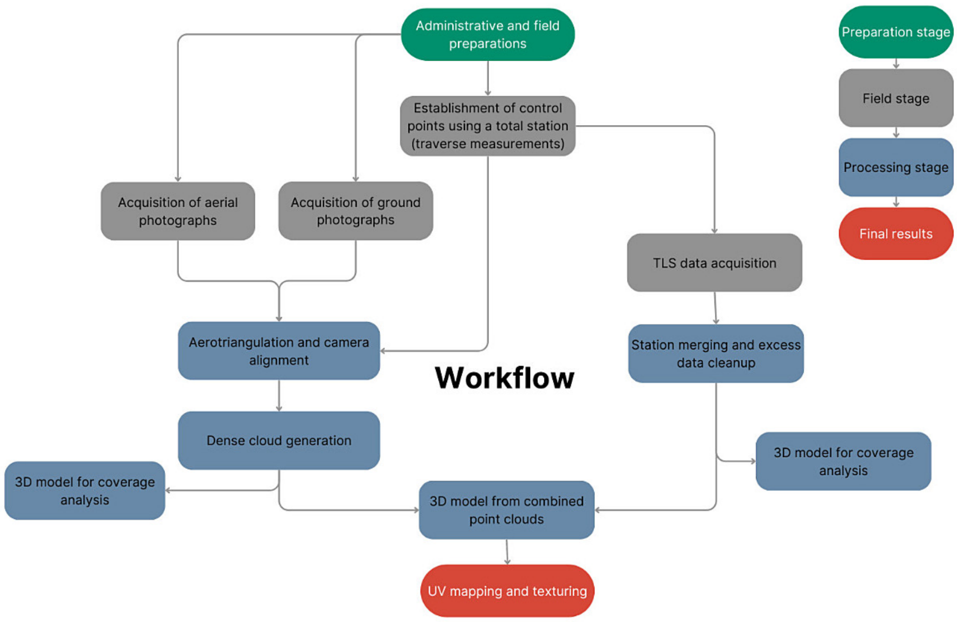


Fig. 2. Block diagram of complete workflow

was a closed traverse, which was connected to the national detailed coordinate grid possessing known horizontal and vertical coordinates. The observations were measured with a TOPCON total station and a mini prism with a constant = +17.5mm. During the survey of the traverse, photopoints were also measured using the radial survey method with mirrorless mode selected. The points were arranged on the facade of the building at characteristic locations and will serve to align the images during the aerotriangulation process. After completing the measurements with geodetic equipment, scanning was carried out. The high accuracy mode was used (distance density between points 6mm at a distance of 30m), and only areas containing the town hall were measured to speed up the work. The drone measurement was carried out by a pilot with NSTS-05 qualifications, allowing flights over people and buildings, and the flight was reported to the Polish Air Navigation Services Agency. The flight was carried out manually, and the 6 camera parameters were set manually as well – due to the drone's matrice with the so-called rolling shutter technology (pixels do not receive light during reading, the exposure area shifts across the sensor, similar to an analog camera with a slit shutter), it was necessary to take pictures at a short exposure time [12] (below 1/400s). In addition, for the highest quality photos, the native ISO value of 100 was used [12]. The photos were taken at two gimbal tilt angles, 0 degrees (horizon) – to capture the details of the building and create a high-resolution texture, and 30 degrees – to create a model of the roof and other places that the terrestrial laser scanner could not reach. 1200 aerial photos of the town hall were taken (Figure 3).

The final stage of the work was taking ground photos with a digital camera. Considering the highest possible quality of the images, the native ISO 100 was used again, along with low exposure times. To obtain the largest depth of field and minimize blurring of objects outside the main frame, the highest aperture values within useful range were used (f = 4.0 for the drone and f = 8.0–10.0 for the camera) [12].

PROCESSING STAGE

All results were processed in geodetic and photogrammetric software (Table 2) on a workstation with 32GB DDR4 RAM, an AMD Ryzen 7 processor, and Nvidia RTX3060Ti 6GB vRAM graphics card. During the survey, 12 control points were established around the area and then measured using a TOPCON ES-105 total station with a closed traverse method connected to the nearby national detailed geodetic network.

The observations were imported into the WinKalk software, where they were calculated and adjusted using the least square adjustment method [22]. Linear errors were determined with values f_x = -17 mm, f_y = -24 mm, which were then used to align the coordinates. The photos taken with a digital camera contain errors related to lack of focus, overexposure, or underexposure of objects [23]. The RAW format, containing a large amount of data for editing, allows for post-processing of the photos and obtaining as much information as possible needed for digitizing [23]. Additionally, utilizing Adobe Lightroom software provides the capability to adjust photos for white balance and color accuracy, ensuring precise and balanced results [23]. The standardized photos were uploaded to Agisoft Metashape and analyzed using the built-in function for estimating their quality in terms of blurriness and depth of field. Due to the accuracy of the future model and texture, photos with an unsatisfactory quality index had to be rejected. In the process of creating the model, 8 photos were removed that did not meet the accuracy requirements.

All photos taken by the drone camera were georeferenced in the WGS84 ellipsoidal coordinate system with a GNSS positioning accuracy of ±1.5 meters [24]. Positions were aligned in the aerotriangulation process which result was a thin point cloud consisting of approximately 2 million tie points. This process allowed for estimation of the image residuals which illustrates the

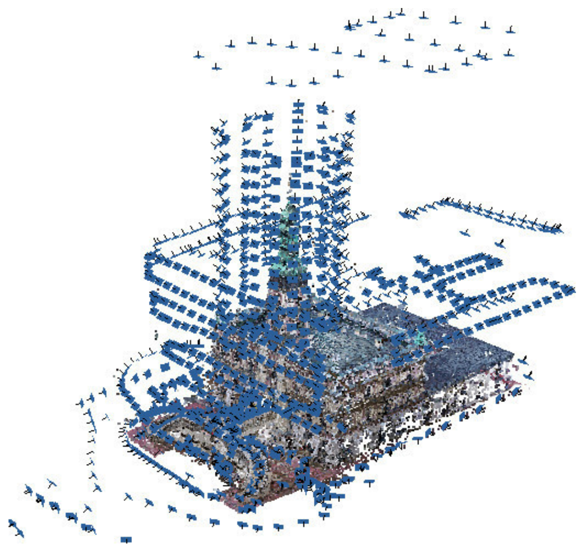
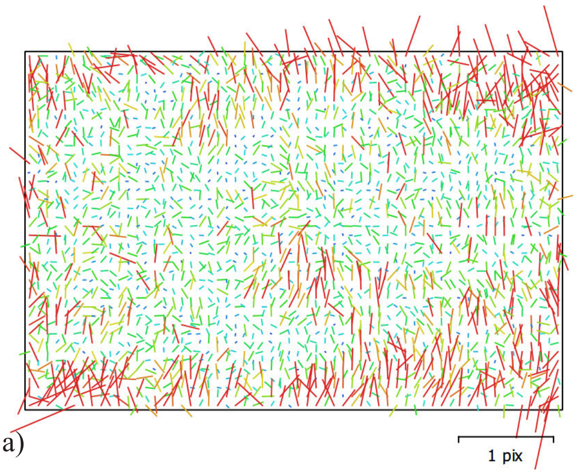


Fig. 3. Location of cameras in relation to city hall (Agisoft Metashape)

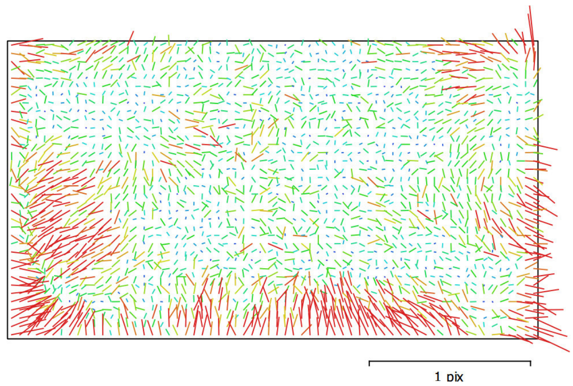
Table 2. Computer software used in the processing of measurement results

Processing stage	Software	Is paid
Traverse calculations	WinKalk v4.1	Yes (30 day trial)
TLS stations calculation	Topcon ScanMaster v3.0	Available with Topcon GLS-2000 scanner
RAW images processing	Adobe Lightroom Classic 2022	Yes (30 day trial)
SfM and data merging	Agisoft Metashape v1.8.5	Yes (30 day trial)

mean vector of reprojection errors pertaining to pixels within their respective cells. This calculation involves averaging across all images within the calibration group and all pixels encompassed by the cell. The image residuals serve as a fundamental measure to evaluate the accuracy of camera calibration, assess the quality of point clouds/model, and verify the alignment of images (Figure 4a, 4b). The next step was to load the text files containing the coordinates of the photopoints and manually mark them on the photos. The points were then classified based on the accuracy of their representation on the image to the surface of the 3D model and filtered to reject inaccurate data. The camera positions were then automatically calibrated, and the aerotriangulation process repeated for the most faithful representation of reality (Table 3). The prepared data could then be subjected to the next process, which is generating a dense point cloud. The obtained cloud consisted of 257 million points and still contained a lot of unnecessary data that needed to be removed. After cleaning the cloud, it was necessary to create a preliminary model based on it and check the coverage of the object using a confidence factor, which indicates whether the object has been properly created. It may show less accurate areas and errors in geometry – the color scale ranges from the least confidence (red), to the highest (blue). Equal color throughout the model indicates uniform coverage and high certainty of the processed object. (Figure 5).



a)



b)

Fig. 4. (a) Image residuals for Canon EOS 6D, Tokina AT-X 16-28 F2.8 PRO FX (24 mm) (Agisoft Metashape); (b) image residuals for L1D-20c, 28.0 mm f/2.8 (10.26mm) (Agisoft Metashape)

Table 3. Errors in the position of points in the images and the number of projections indicating the visibility of a control point from multiple photos - state of pre-transformation (errors come from GNSS positioning accuracy) and after the transformation with camera calibration and optimization performed

Control point	Pre-transformation		After transformation		Projections
	Error [m]	Error [pix]	Error [m]	Error [pix]	
1	0.904	7.252	0.007	0.432	50
2	1.585	9.798	0.006	0.374	44
3	2.072	18.201	0.001	0.129	214
4	0.461	2.852	0.003	0.213	46
5	2.277	13.300	0.006	0.414	193
6	1.556	11.651	0.013	0.839	65
7	1.334	8.271	0.005	0.301	285
8	1.083	8.802	0.006	0.362	30
9	1.765	10.301	0.011	0.654	281
10	2.750	21.159	0.002	0.155	206
11	0.948	5.384	0.001	0.114	118
12	1.458	10.136	0.006	0.386	39

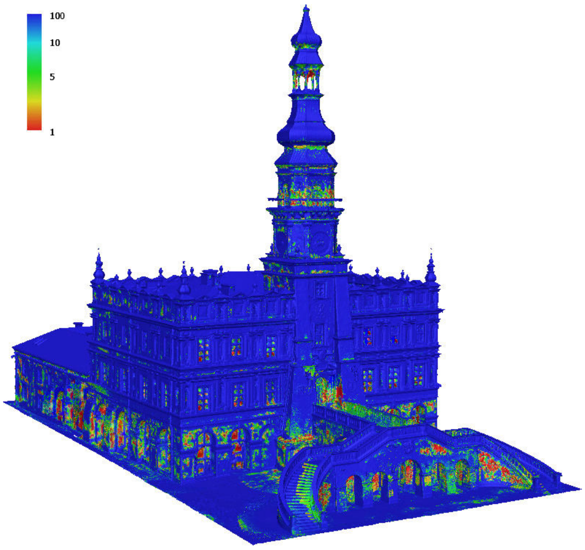


Fig. 5. Model confidence [%] – photogrammetry data (Agisoft Metashape)

The analysis of the model's density showed that the model accurately and uniformly reflects the town hall object, and the dense point cloud can be merged with the point cloud obtained from the terrestrial scanner. The next step was the processing of results from the terrestrial laser scanner. The instrument positions had to be calculated and combined into a final point cloud. All acquired data was imported into the ScanMaster software by TOPCON, where a text file with coordinates was uploaded and the coordinates of each point were calculated. To verify the accuracy of this process, 4 corresponding points were selected from the overlapping instrument stations (Table 4)

The merged point cloud was also colored using panoramic images taken by the TLS during scanning. Prepared point cloud was exported to the .LAS format and loaded into the Metashape software. The raw data contained large amounts of additional and unnecessary information that had to be removed (Figure 6a, 6b). A 3D model was constructed using the point cloud obtained from the scanner to examine it for errors and distortions. The coverage coefficient was utilized once again, revealing errors and inconsistencies in areas that posed challenges for TLS access. Furthermore, it highlighted overlapping instrument stations data (Figure 7).

By using common control points and the same coordinate systems – the horizontal PL-2000'24 and vertical PL-EVRF2007-NH – the point cloud from the digital images was overlaid on the data from the terrestrial scanner. At this stage, the positions of characteristic points of the object were analyzed from both different sources. For comparison purposes, 9 points were selected

Table 4. Differences in the coordinates of selected points acquired from overlapping terrestrial laser scanner positions

Point	ΔX [m]	ΔY [m]	ΔH [m]
1	-0.002	0.003	0.002
2	0.007	0.004	0.002
3	-0.002	0.005	-0.004
4	0.004	-0.005	-0.001

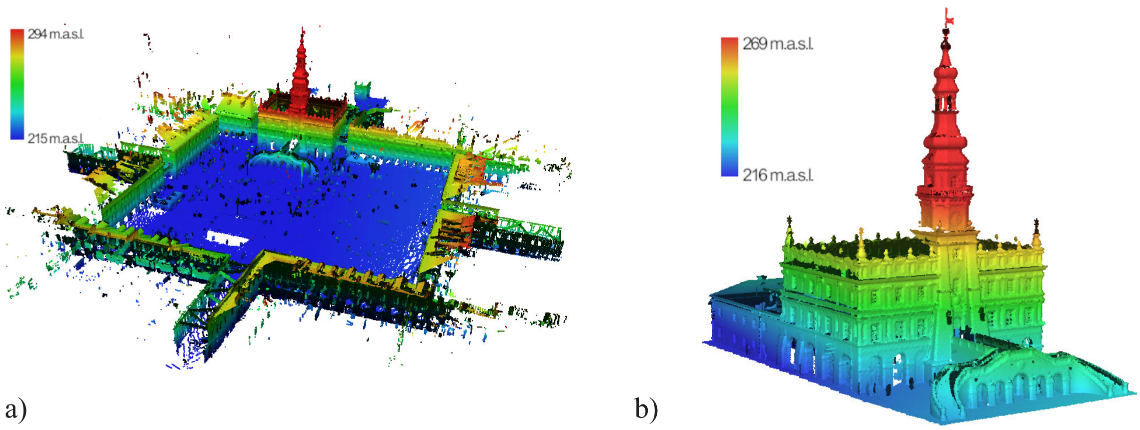


Fig. 6. (a) Point cloud before cleaning, elevation-classified data – TLS (Agisoft Metashape) (b) Point cloud after cleaning, elevation-classified data – TLS (Agisoft Metashape)

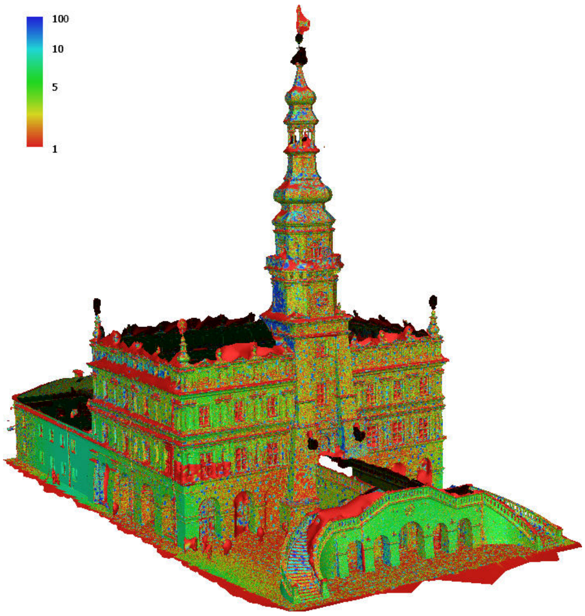


Fig. 7. Model confidence [%] – TLS data (Agisoft Metashape)

sequentially: at the corners of the town hall roof, at the tip of the eagle (the emblem below the tower) on the control point, and at the top of the town hall tower (Table 5).

The final step was to create a model based on the combined point clouds. The process took 4 hours and resulted in a triangle mesh generated using an improved Delaunay triangulation algorithm, which provides the best representation of reality and ensures that each created triangle has the smallest possible angles [25]. To cover the mesh with such a large number of points, a modified 3D S-HULL algorithm was used, which is a significant technological leap from the original algorithm, resulting in a mesh consisting of 69 million elements [26]. The obtained model (Figure 8a, 8b) was then filtered and smoothed with a power coefficient of 0.25 to obtain smooth, non-frayed faces without artifacts [27]. Coverage analysis was carried out again, which showed that

Table 5. The differences in coordinates of corresponding points between the TLS data and the point cloud derived from digital images

Point	ΔX [m]	ΔY [m]	ΔH [m]
1	-0.018	0.016	-0.028
2	0.022	0.016	-0.012
3	-0.015	0.024	-0.018
4	0.017	-0.026	-0.028
5	-0.021	0.019	-0.026
6	0.014	-0.016	-0.019
7	-0.012	0.013	0.009
8	-0.007	0.003	0.005
9	0.017	0.009	-0.039

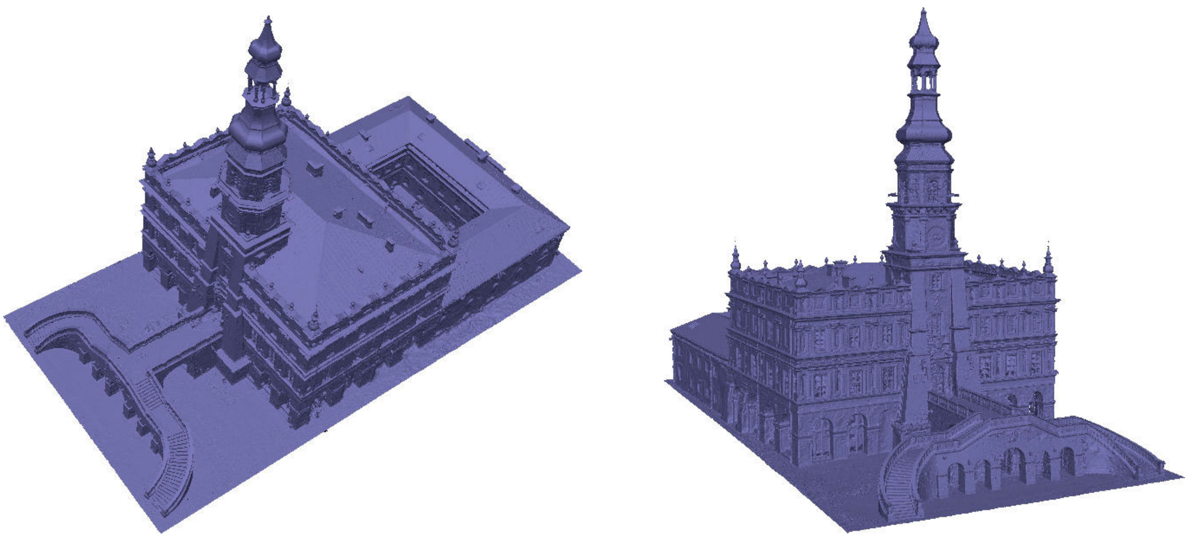


Fig. 8. Model based on the combined point clouds, without texturing (Agisoft Metashape)

the town hall was accurately and evenly reflected without errors in mesh density (Figure 9). The only remaining process in digitizing procedure was generating textures. Images obtained from an unmanned aerial vehicle and a digital camera were used for this purpose. During this process, the 3D model was divided into parts and projected onto a plane, creating two-dimensional maps [28]. Each smallest surface of the model had assigned coordinates in the UV grid, adapted to a resolution of 8192x8192 [28]. To accurately cover the study area, 5 textures were generated (each with dimensions of 8192x8192). Colors of individual pixels were obtained from multiple photos taken at different angles to the model surface, and then unified and blended with the surroundings [29, 30]. The resulting textures accurately reflect the actual color of the Town Hall (Figure 10a, 10b). Details concerning the individual stages of measurement and processing are presented in Table 6.

The combination of data from photogrammetric surveys and TLS point clouds allows for the creation of a comprehensive 3D model with high quality and minimal discontinuities. This approach offers notable advantages, such as the high data density and centimeter-level accuracy(Table 7), which surpasses traditional photogrammetric methods in terms of efficiency and quality. Integrating data from multiple sources provides a more detailed representation of the building. Analyses have demonstrated that data obtained through these methods can deliver geodetic products with high accuracy while adhering to specific guidelines.

The precision assessment of both ground control point (GCP)-based technologies was rigorously conducted. Laser scanning consistently exhibited superior positioning accuracy compared to photogrammetry(Table 7). This discerned differentiation between the two technologies facilitated the generation of convergent data. Subsequently, integrating the photogrammetric point cloud data with the laser scanning results, effectively enhances the 3D model, particularly in areas of the building that were challenging for terrestrial laser scanning due to their limited accessibility. The low RMSE values for photogrammetry achieved in our study may result from increased measurement precision or the utilization of more advanced and refined software versions, which is reflected in greater accuracy of the results compared to those obtained in [31, 32]. V2. The obtained RMSE errors with respect to

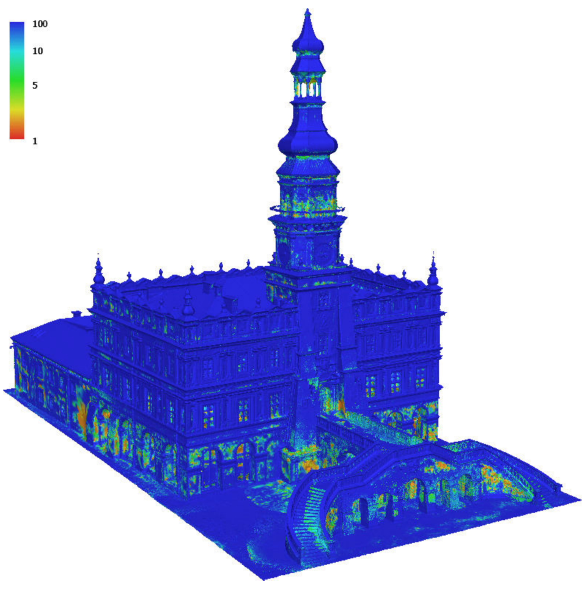


Fig. 9. Model confidence levels – combined methods (Agisoft Metashape)

Fig. 10. Model based on the combined point clouds, with texturing (Agisoft Metashape)

Table 6. Individual stages with detailed parameters and execution time

No.	Process	Settings	Additional information	Processing time
1	Control points establishment	-	-	2h 30min
2	Data acquisition: UAV and ground photos	ISO: 100	1000 aerial photos	0h 50min
		f = 4.0 for the drone		
		f = 8.0-10.0 for the camera	400 ground level photos	
3	Data acquisition: scanning	Scanning resolution: 6mm up to 30 meters	Time required for a single 360° scan: 10 mins	1h 20min
4	Postprocessing: Aerotriangulation	Accuracy: high	Number of tie-points: 2000000	9h 20min
		Generic preselection: yes		
		Key point limit: 60000		
		Tie point limit: 5000		
5	Postprocessing: camera alignment using control points	Control points: 12	-	0h 20min
		Photopoints: 20		
		Optimization corrections: f, k1, k2, k3, k4, cx, cy, p1, p2, b1, b2		
6	Postprocessing: depth maps and 3D model generation	Depth quality: high	Single GPU processing	6h 40min
		Face count: high		
		Interpolation: enabled		
		Depth filtering: moderate		
7	Postprocessing: calculation of scanner positions	Export file type: .las	Point count: 11000000	0h 30min
8	Postprocessing: 3D model from LIDAR data	Recalculating normals: yes	-	1h 10min
		Interpolation: enabled		
		Face count: high		
9	Postprocessing: 3D model from combined data sources	Interpolation: enabled	Export format: .fbx	1h 30min
		Face count: high		
10	Postprocessing: UV mapping and textures creation	Texture count: 5	JPEG with 90% compression	1h 50min
		Texture size: 8192x8192		
		Blending mode: Mosaic	Total files size: 150 mb	
		Fill holes: yes		
		Ghosting filter: yes		

Table 7. Accuracy analysis – the root-mean-square error calculated from the linear deviations obtained from the difference in position of the photopoints to corresponding points acquired by terrestrial scanner and photogrammetry

Photopoint	Photopoint - TLS cloud data				Photopoint - photogrammetry dense cloud			
	ΔX [m]	ΔY [m]	ΔH [m]	magnitude	ΔX [m]	ΔY [m]	ΔH [m]	magnitude
1	0.001	-0.002	0.006	0.006	0.017	-0.011	0.019	0.028
2	0.009	0.004	-0.002	0.010	-0.015	0.013	-0.016	0.025
3	0.008	-0.007	-0.001	0.011	0.013	-0.002	-0.007	0.015
4	-0.008	0.007	-0.002	0.011	0.014	0.024	-0.016	0.032
5	-0.007	-0.005	0.009	0.012	0.016	-0.017	0.020	0.031
6	-0.005	0.004	0.007	0.009	-0.002	0.010	-0.017	0.020
7	0.004	0.006	0.001	0.007	-0.001	0.001	0.006	0.006
8	0.004	0.007	0.000	0.008	-0.016	-0.014	-0.015	0.026
9	-0.003	0.004	0.006	0.008	-0.013	0.013	0.012	0.022
10	-0.001	0.009	-0.002	0.009	0.011	0.006	0.012	0.017
	RMSE			0.009	RMSE			0.023

the photopoints display similar accuracy to the results obtained in [32]. However, our work features greater precision than [31], which may be due to more precise measurement or a newer version of the used computer software. Obtaining different data opens the doors to further work on improving the accuracy of photogrammetric studies. There are many areas that could be further

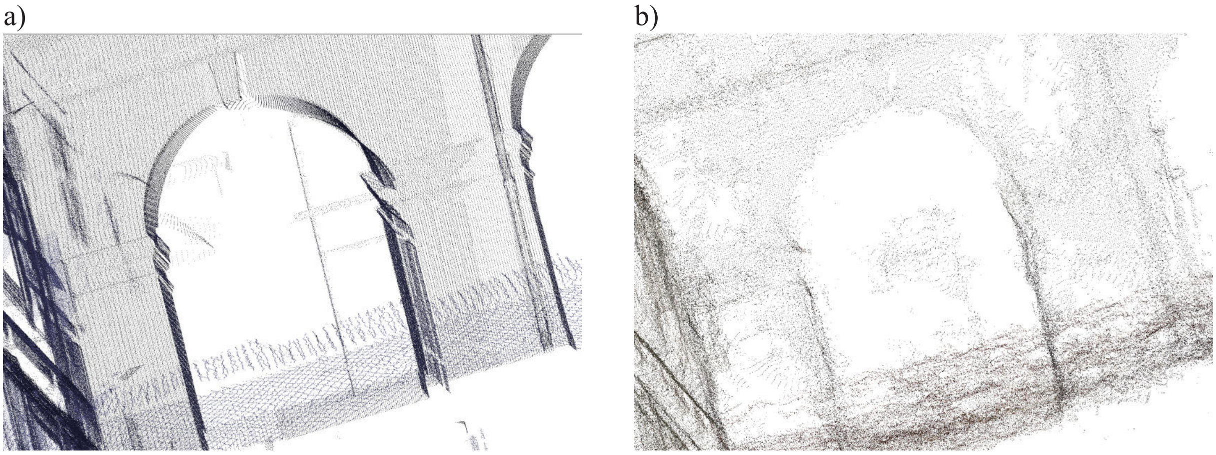


Fig. 11. (a) Part of point cloud from TLS showcasing the arcade of Zamość Town Hall (Agisoft Metashape), (b) part of point cloud from photogrammetric data showcasing the arcade of Zamość Town Hall (Agisoft Metashape)

developed to optimize processes and achieve even higher precision in results.

DISCUSSION

The processing results clearly reveal the advantages and limitations present in both methods of three-dimensional model creation as also discussed in [33]. One notable challenge was the limited mobility of the terrestrial laser scanner, which posed difficulties in capturing measurements in hard-to-reach areas of the building. This limitation necessitated the use of aerial photogrammetry techniques with a drone to complement the data collection process [34, 31]. TLS and photogrammetric techniques were found to be complementary similar to [11, 32]. The main and most noticeable issue in both cases is the presence of glazing and highly reflective surfaces. These challenges predominantly occur in large glass windows and facade windows on the town hall elevation [28]. A distinct advantage of laser scanning is the generation of a regular and accurate point cloud dataset (Fig. 11a), which is not achievable in photogrammetry with an insufficient number of images (Fig. 11b) [17, 34, 35]. Significant problems arise in models made from photographs, particularly on surfaces with a highly uniform color and low roughness, such as facades, leading to irregularities in the point clouds and meshes.

The mentioned issues adversely affect the texturing of the model. Reflective surfaces and their immediate surroundings are not consistently represented. The textures additionally exhibit burnt-in shadows and ambient occlusion [36, 37] resulting from non-uniform lighting conditions during data acquisition.

CONCLUSIONS

With appropriate guidelines, the combination of TLS technology with photogrammetry allows you to obtain centimeter data of geodetic quality (despite small discrepancies in accuracy, data fusion allows you to obtain a consistent 3D model, average RMSE 0.016 m). The conducted work has shown that the use of unmanned aerial vehicles in combination with digital cameras allows for obtaining data from locations inaccessible to terrestrial laser scanners, which is cheaper than the purchase of airborne scanners. To achieve similar modeling effects, basic knowledge of both technologies, digital cameras, post-processing and others is necessary. Challenges emerged from the drone's rolling shutter camera, requiring precise adjustments in exposure and ISO settings to avoid focus issues and over/underexposure. Post-processing involved meticulous photo selection and rejection to meet accuracy standards, affecting workflow efficiency.

The speed of data acquisition for such a large facility (approx. 4 hours of field work) gives an advantage over classic measurement methods, which facilitates work in crowded facilities, in changing weather conditions, etc. Limited equipment mobility and visibility posed challenges for capturing thin object details like railings, spires, and fine features. It is possible to use older equipment, but it is important to be aware of its limitations and know the technology that can support it. The resulting model is a great base for further conservation activities and historians. In conclusion, usage of drones is currently one of the most effective ways of acquiring and supplementing geodetic data. UAVs facilitate efficient and expeditious access to otherwise inaccessible terrains, thus enabling the acquisition of extensive datasets surpassing the limitations of conventional terrestrial surveying techniques, including ground-based laser scanning.

Despite using equipment available for several years, it proved reliable, providing single-centimeter-level accuracy. The UAV excelled in maneuverability, granting access to challenging sites. The digital camera captured high-quality images, fine-tuned for accurate digitization. Despite its age, the Topcon GLS-2000 was effective, showcasing the value of established technology when well-planned. The resulting detailed 3D model aided architectural analysis and conservation. This hybrid method saved time and improved result quality, aiding in documenting the historic building comprehensively. A complete, three-dimensional model of a historical object is an excellent basis for future reconstructions and repairs. It allows for preserving cultural heritage for future generations in a different form than two-dimensional photography.

Acknowledgment

The authors would like to thank the University of Life Sciences in Lublin for the financial support provided for this research to the Geodetic Science Club „Equator", as part of the competition of science clubs of the University of Life Sciences in Lublin in 2022. The authors would like to thank Dr. Eng Radomir Obroslak for his great help with the field measurements.

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