

Three-dimensional modelling of a historic townhouse at the Market Square in Przemyśl (Rynek 11) using terrestrial laser scanning and photogrammetry

Przemysław Leń¹,  0000-0003-0810-9986

Karol Ożóg²  0000-0002-2464-9010

Klaudia Maciąg³  0000-0003-4099-9886

Michał Maciąg³  0000-0002-8745-0009

¹ Department of Geodesy and Geotechnics, Faculty of Civil and Environmental Engineering and Architecture, Rzeszów University of Technology

² Vice-Marshall of the Podkarpackie Voivodeship, Marshall's Office of the Podkarpackie Voivodeship

³ Department of Geodesy and Spatial Information, University of Life Sciences in Lublin

 Corresponding author: p.len@prz.edu.pl

Summary

This paper presents the development of a three-dimensional model of a historic townhouse located at the Market Square (Rynek 11) in Przemyśl using data acquired by terrestrial laser scanning (TLS) and terrestrial and aerial photogrammetry. The study aimed to assess the usefulness of an integrated measurement approach for preparing detailed architectural documentation of a heritage building and to evaluate the quality of the final products, including the point cloud, mesh model, vector 3D model, and orthophotos. The methodology entailed field surveying, multi-station registration, georeferencing in the PL-2000 coordinate system, data filtering and cleaning, and subsequent processing in specialised software. The integrated workflow combined the geometric precision of TLS with the visual richness of image-based modelling. The results demonstrated that the adopted approach enabled the acquisition of highly detailed and metrically reliable documentation of the object. The final point cloud consisted of 1.617 billion points, while the mean registration error remained below 1 mm. The generated mesh model and vector model showed high geometric consistency with the source data, and the orthophotos made it possible to identify architectural details, material features, cracks, losses, and traces of previous repairs. The study confirms that the integration of TLS and photogrammetry provides an effective

tive basis for digital documentation of historic buildings and that it may support conservation, restoration planning, archiving, and further design work.

Keywords

terrestrial laser scanning • photogrammetry • point cloud • 3D model • orthophoto • cultural heritage

1. Introduction

Digital documentation of historic objects is currently one of the most important directions in the development of engineering geodesy, geomatics and cultural heritage studies [Kurczyński 2006, Kurczyński 2014, Wężyk 2006]. The use of terrestrial laser scanning and photogrammetry enables fast acquisition of highly detailed spatial data and their subsequent application for creating metric 3D models, orthophotos and conservation documentation [Kurczyński 2006, Kurczyński 2014, Wężyk 2006]. In the international literature, these technologies are indicated as basic tools for the inventory of historical objects, reconstruction of building geometry and monitoring of their technical condition [Rodríguez-Moreno et al. 2018, Remondino and Campana 2014, Tucci et al. 2017].

The importance of integrating different measurement techniques is particularly evident in the case of historic buildings with complex geometry and limited accessibility of some façade and roof sections. In such instances, terrestrial scanning ensures high accuracy in representing details and surfaces accessible from ground level, whereas terrestrial and aerial photogrammetry complement the information on hardly accessible zones and provide material for texturing spatial models [Kurczyński 2014, Schenk 2005, Zaczek-Peplińska and Strach 2017]. Similar research directions are also undertaken in the Polish literature, where the role of modern measurement techniques in spatial documentation, analyses of historic objects and creation of reliable spatial databases for spatial management is emphasised [Kwoczyńska et al. 2023, Kwoczyńska and Gudź 2023, Kłapa et al. 2023, Piech and Cieśla 2024]. In particular, the high usefulness of integrating TLS, ALS and UAV data in 3D modelling of historic objects and the applicability of photogrammetric methods in the documentation and inventory of heritage buildings are highlighted [Kwoczyńska et al. 2023, Kwoczyńska and Gudź 2023, Kłapa et al. 2023, Piech and Cieśla 2024].

The present paper addresses these issues by presenting an integrated TLS–photogrammetry approach applied to a historic townhouse located at the Market Square in Przemyśl (Rynek 11).

2. Aim and research problem

The main aim of the study was to develop and evaluate the usefulness of a detailed three-dimensional model of a historic townhouse at the Market Square (Rynek 11) in Przemyśl, created on the basis of integrated data acquired by terrestrial laser scanning and terrestrial and aerial photogrammetry [Kurczyński 2014, Zaczek-Peplińska and

Strach 2017, Kwoczyńska et al. 2023, Kwoczyńska and Gudź 2023]. The application-oriented goal was to verify whether the obtained final products can constitute complete architectural documentation of the object for further design, conservation and archival works [Kurczyński 2014, Zaczek-Peplińska and Strach 2017, Kwoczyńska et al. 2023, Kwoczyńska and Gudź 2023].

Accordingly, the following research problem was formulated: to what extent does the integration of laser scanning and photogrammetric data enable the preparation of detailed, geometrically correct and practically useful documentation of a historic urban townhouse? The following detailed questions were also posed: (1) what is the quality and completeness of the point cloud obtained, (2) is it possible to generate a mesh model and a 3D model with high geometric consistency with the source data, (3) do the façade and roof orthophotos provide sufficient information for monument conservation analyses, and (4) what are the practical benefits and limitations of the adopted methodology?

3. Study object

The study object was a historic townhouse located at the Market Square in Przemyśl (Rynek 11), in the historic city centre, within the urban complex of the Old Town listed in the heritage register [Frazik 1971]. The building is listed in the register of monuments under number A-306 and falls within monument conservation protection zone 'A' of the Przemyśl urban layout (no. A-1493). The building represents a valuable example of the burgher architecture of Przemyśl; it was most probably erected in the mid-sixteenth century during the city's greatest economic prosperity, when wealthy burghers rebuilt their houses in the Renaissance style following Italian architectural models [Frazik 1971]. The townhouse was constructed with the participation of Italian master builders settled in the city, among them Andrzej (Andrea) Peregryno Bononi and Piotr (Pietro) Włoch de Ponto. Originally single-storey, as was typical of sixteenth-century Przemyśl burgher architecture, the building was extended upward in subsequent periods and also originally featured arcades serving commercial purposes. A particularly distinctive feature is the preserved traces of sgraffito decoration on the façade – only two townhouses in the Przemyśl market square retain visible remains of this decorative technique: no. 11 and no. 16. The building was the subject of detailed architectural research conducted by Professor Józef Frazik (1922–1998) of the Cracow University of Technology, the results of which were published in 1971 [Frazik 1971]. The structure has undergone numerous reconstructions and is currently being adapted to serve as a new seat of an art gallery, which additionally justifies the need for detailed geometric and visual documentation.

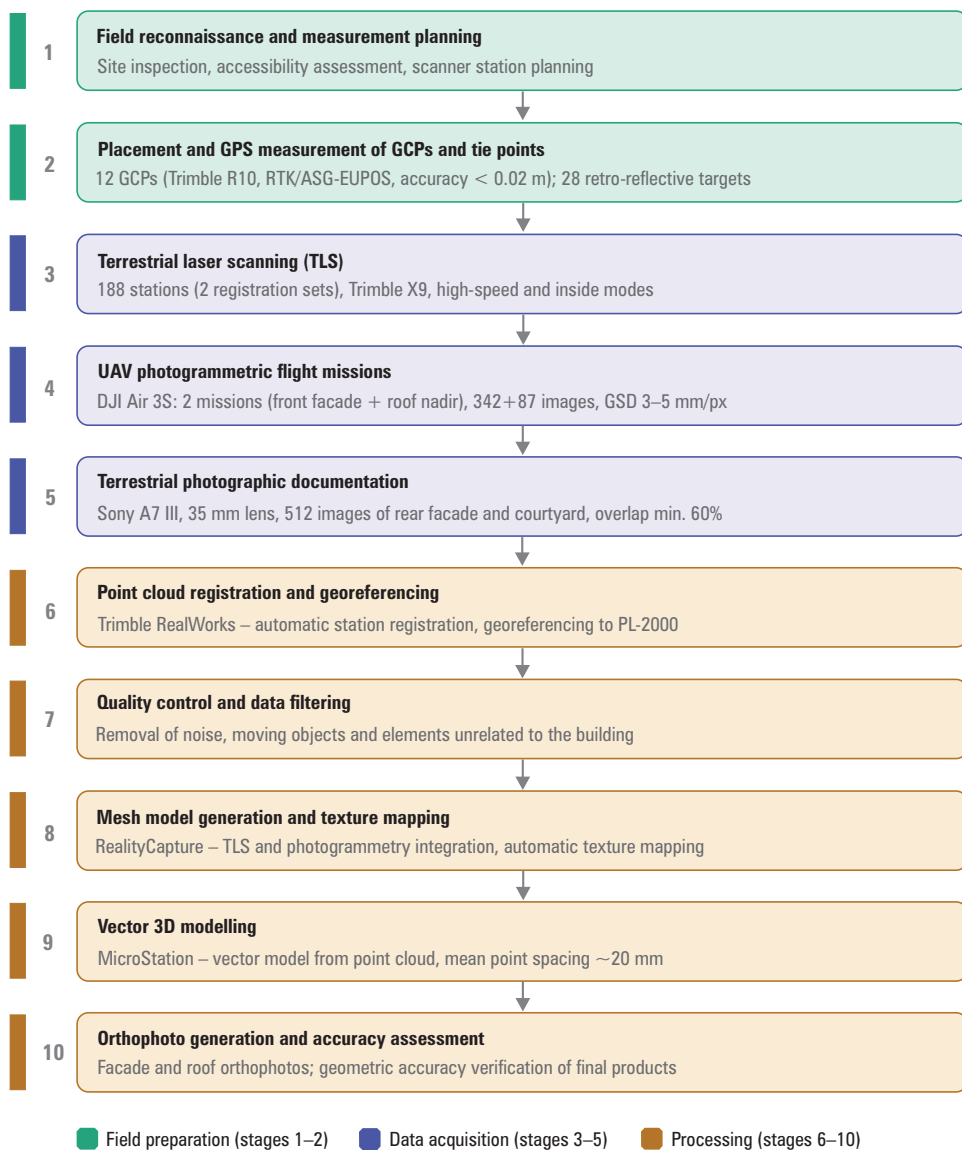
The townhouse is situated on the eastern side of the main square in Przemyśl, which constitutes an area of high historical, urban and conservation value. The market square was laid out under Magdeburg law in the second half of the fourteenth century on a plan approximating a square with sides of approximately 80 metres. A distinctive feature of the Przemyśl market square is its sloping terrain, which sets it apart from

other medieval town squares in Poland and gives it a unique visual character. In the centre of the square once stood a Renaissance town hall erected in the mid-sixteenth century by Italian architect Andrzej (Andrea) Bononi, demolished in 1794 on the orders of the partitioning authorities. The entire Old Town urban complex was recognised as a Historic Monument on 10 December 2018 by decree of the President of the Republic of Poland, underscoring the exceptional historical and architectural value of the ensemble, including the townhouse at no. 11 in the Market Square. Przemyśl itself is situated on the Przemyśl Foothills in the San river valley, spread across seven hills at an average elevation of approximately 220–230 m above sea level, some 15 km from the Ukrainian border, with a population of around 55,000 inhabitants. From the perspective of geodetic and photogrammetric research, the object is characterised by a complex shape, the presence of architectural details and observational limitations resulting from dense urban development. These conditions make it an appropriate example for assessing the effectiveness of methods integrating laser scanning and photogrammetry.

4. Material and methods

4.1. Methodological assumptions

The study applied a case study approach, appropriate for analyses concerning detailed documentation of a single historic object [Kurczyński 2006, Kurczyński 2014, Schenk 2005, Kwoczyńska and Gudź 2023, Piech and Cieśla 2024]. An integrated approach was adopted, combining data acquired in the field using 3D terrestrial laser scanning with photographic material collected from ground level and from a UAV platform [Kurczyński 2006, Kurczyński 2014, Schenk 2005, Kwoczyńska and Gudź 2023, Piech and Cieśla 2024]. From the research perspective, the procedure entailed data acquisition, georeferencing, registration of point clouds, quality control, data cleaning, spatial modelling and analysis of final products [Kurczyński 2006, Kurczyński 2014, Schenk 2005, Kwoczyńska and Gudź 2023, Piech and Cieśla 2024]. The method had an empirical–analytical character, combining direct field data acquisition with accuracy assessment and evaluation of the usefulness of the resulting products for architectural and conservation documentation. The overall research workflow comprised the following sequential stages: (1) preliminary field reconnaissance and measurement planning, (2) placement and GPS measurement of ground control points (GCPs) and tie points, (3) terrestrial laser scanning from multiple stations, (4) UAV mission planning and execution of aerial photogrammetric flights, (5) terrestrial photographic documentation, (6) point cloud registration and georeferencing, (7) quality control and data filtering, (8) mesh model generation and texture mapping in RealityCapture, (9) vector 3D modelling in MicroStation, and (10) orthophoto generation and accuracy assessment of final products. The logical sequence of these steps is presented in Figure 1 (workflow diagram). Each stage was conditioned by the results of the preceding one, which ensured consistency of the integrated dataset and enabled systematic quality control throughout the entire process.



Source: Authors' own study

Fig. 1. Workflow diagram of the integrated TLS and photogrammetry methodology. Stages 1–2 relate to field preparation, stages 3–5 to data acquisition, and stages 6–10 to office processing and accuracy assessment of the final products

4.2. Field data acquisition

Field work was divided into two main stages: terrestrial scanning and photogrammetric documentation. The terrestrial survey covered the external façades and the interior of the building, and scanning was performed from 188 stations grouped into two registration sets, which resulted from the complex geometry of the object, the need to eliminate occlusions and the pursuit of full coverage of accessible surfaces. Prior to scanning, a network of ground control points (GCPs) and tie points was established around the building. A total of 12 GCPs were measured using a Trimble R10 GNSS receiver in RTK mode with reference to the ASG-EUPOS network, achieving positional accuracy better than 0.02 m. The GCPs were distributed evenly around all four elevations of the building and placed on stable, clearly identifiable elements of the surrounding pavement and walls. In addition, 28 tie points in the form of retro-reflective targets were mounted on the building's façades at heights between 0.5 m and 3.0 m above ground level, enabling precise inter-station registration and georeferencing of the point cloud into the PL-2000 coordinate system. The spatial distribution of GCPs and tie points was designed to minimise registration errors and ensure full geometric control of the final dataset. Scanning stations were arranged so that neighbouring stations shared an overlap of at least 30% of their scan data, and the mean distance from scanner to the closest façade surface did not exceed 15 m, ensuring the target point density of approximately 4 mm at the façade surface in high-speed mode.

In parallel, photographic documentation was performed using a Sony A7 III camera and a DJI Air 3S UAV, with particular focus on the front façade and roof, i.e. parts that are important from the viewpoint of representational values and are more difficult to access [Piech and Cieśla 2024, Kłapa et al. 2023]. Such a solution corresponds to research indicating the high effectiveness of photogrammetric data in measurement, control and documentation tasks [Piech and Cieśla 2024, Kłapa et al. 2023]. The UAV flight missions were planned and executed using DJI Pilot 2 software. Two separate flight missions were carried out: the first covered the front (eastern) façade at a standoff distance of 8–12 m with the camera gimbal tilted at 75° from horizontal, and the second was a nadir mission over the roof surface at an altitude of 25 m above the ridge level. The front façade mission consisted of six parallel flight lines with 80% forward overlap and 70% side overlap, resulting in 342 images at a ground sampling distance (GSD) of approximately 3 mm/pixel. The roof nadir mission produced 87 images with 85% forward overlap and 80% side overlap at a GSD of approximately 5 mm/pixel. Ground-level terrestrial photography of the rear (western) façade and courtyard elevations was acquired using the Sony A7 III camera with a 35 mm full-frame lens, producing 512 images with a minimum 60% overlap between adjacent frames. All photographic missions used the previously measured GCPs as reference points for image orientation and bundle adjustment. To georeference the data, direct GPS measurements were carried out for characteristic terrain points identifiable both in the scans and in the surroundings of the object, which enabled transformation of the data into the PL-2000 coordinate system.

4.3. Office data processing

Data processing started in Trimble RealWorks, where automatic registration of stations was verified and the point cloud was cleaned of noise, moving objects and elements unrelated to the documented building. This stage was particularly important due to the inner-city location of the object and the presence of disturbances such as pedestrian and vehicle traffic or temporary street furniture. After preparing the source data, the point cloud was used in MicroStation to develop a vector model, while the main photorealistic mesh model was generated in RealityCapture. Integration of the point cloud with images enabled creation of a mesh model and texture mapping. This approach corresponds to solutions described in GLL, where integration of TLS and UAV data has been indicated as an effective basis for modelling objects with complex geometry [Kwoczyńska et al. 2023, Kwoczyńska and Gudź 2023]. In the next step, façade and roof orthophotos were generated, constituting final products of high documentary value.

5. Results

5.1. Point cloud

The primary result was a cleaned and registered point cloud acquired using a Trimble X9 terrestrial laser scanner. The final dataset contained 1.617 billion points, which confirms very high density and detail of the documentation. The mean registration error of stations was below 1 mm, with values typically ranging from approximately 0.5 to 0.7 mm, which should be regarded as a very good result for architectural documentation of historic objects. The average inter-station overlap across the analysed registration reports reached 44 percentage points, while the consistency index at every station was 100%, confirming that measurements were carried out without unwanted obstructions. The distances between adjacent scanning stations were small, generally on the order of approximately 5 m. Interior scanning was conducted in the 'Inside' mode, yielding an average point spacing of about 15 mm at a distance of 10 m, while external measurements were performed in the "high speed" mode, with point spacing of approximately 4 mm at the same distance. The mean point spacing did not exceed 20 mm, which allowed representation of details such as cornice profiles, window frames and façade decorations, and the qualitative analysis confirmed full coverage of all accessible surfaces, with minor gaps only in zones entirely inaccessible from ground level.

Interpretation of the results indicates that the high quality of the point cloud resulted both from the large number of stations and from an appropriate measurement strategy adapted to the complexity of the building. In practical terms, this means that the dataset may be treated not only as source material for further modelling, but also as an independent measurement base for geometric, inventory and diagnostic analyses.

177	8 Links	0.5 mm Mean error	51 % Mean overlap	100 % Mean consistency	
	Connected station	Error (mm)	Overlap (%)	Consistency (%)	Distance (m)
	20	0.6 mm	29 %	100 %	3.104 m
	21	0.6 mm	50 %	100 %	5.307 m
	22	0.5 mm	62 %	100 %	2.884 m
	24	0.5 mm	35 %	100 %	2.469 m
	176	0.4 mm	81 %	100 %	1.352 m
	178	0.4 mm	63 %	100 %	1.907 m
	179	0.5 mm	66 %	100 %	2.071 m
	180	0.5 mm	24 %	100 %	2.731 m

Source: Authors' own study

Fig. 2. Registration report for station 177

146	9 Links	0.5 mm Mean error	37 % Mean overlap	100 % Mean consistency	
	Connected station	Error (mm)	Overlap (%)	Consistency (%)	Distance (m)
	34	0.5 mm	31 %	100 %	7.958 m
	68	0.5 mm	25 %	100 %	4.437 m
	90	0.5 mm	29 %	100 %	2.739 m
	91	0.4 mm	64 %	100 %	2.128 m
	92	0.4 mm	45 %	100 %	2.083 m
	93	0.6 mm	32 %	100 %	4.609 m
	110	0.5 mm	26 %	100 %	4.267 m
	144	0.4 mm	36 %	100 %	4.114 m
	145	0.5 mm	40 %	100 %	3.503 m

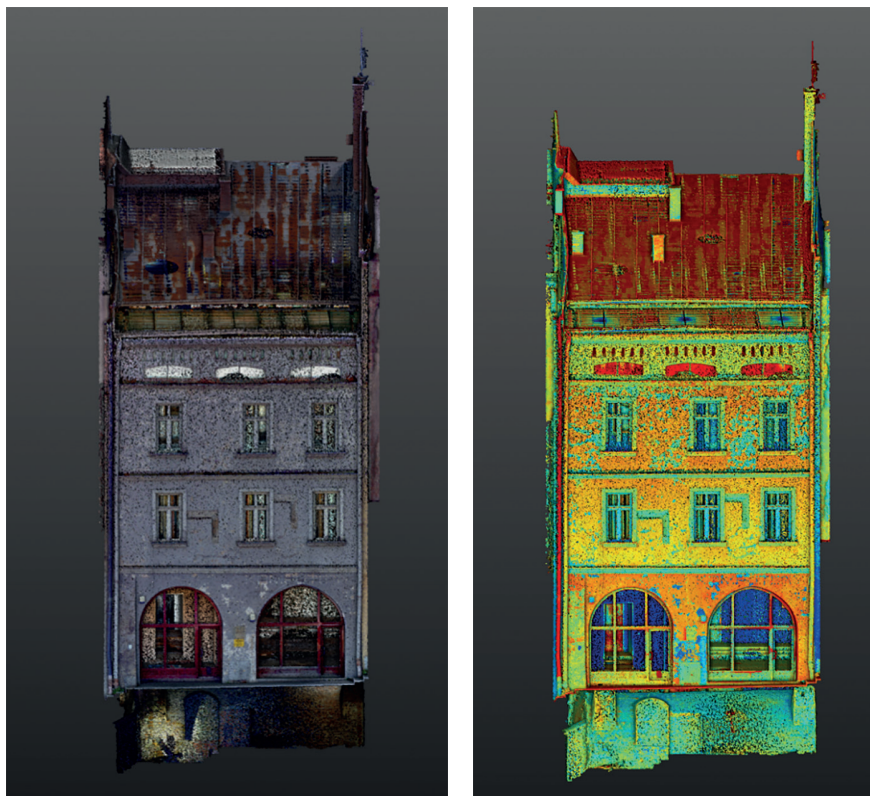
Source: Authors' own study

Fig. 3. Registration report for station 146

42	7 Links	0.7 mm Mean error	44 % Mean overlap	100 % Mean consistency	
	Connected station	Error (mm)	Overlap (%)	Consistency (%)	Distance (m)
	40	0.5 mm	38 %	100 %	3.985 m
	41	0.5 mm	62 %	100 %	2.648 m
	43	0.5 mm	72 %	100 %	4.442 m
	44	0.7 mm	37 %	100 %	7.089 m
	47	0.8 mm	36 %	100 %	7.657 m
	48	0.7 mm	41 %	100 %	6.078 m
	49	1.1 mm	24 %	100 %	8.565 m

Source: Authors' own study

Fig. 4. Registration report for station 42

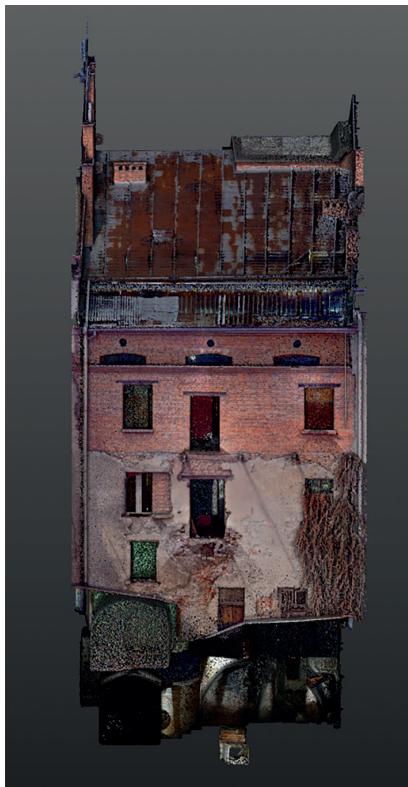


Source: Authors' own study

Fig. 5. Point cloud in Trimble RealWorks: (a) RGB view, (b) laser beam intensity view

5.2. Mesh model

The 3D mesh model was created in RealityCapture using integrated data from laser scanning and terrestrial and aerial photogrammetry. The photographic material was acquired with a Sony A7 III camera for ground-level documentation and a DJI Air 3S UAV for aerial coverage of the front façade and roof. RealityCapture performed automatic image orientation and alignment with the point cloud, combining the geometric precision of TLS with the high visual quality of the photographic documentation. The resulting mesh consisted of many millions of triangles, providing an appropriate level of detail while maintaining practical usability for design and presentation purposes. A key element was automatic texture mapping based on high-resolution images, which enabled photorealistic representation of the building surfaces. The analysis demonstrated high geometric consistency of the mesh with the point cloud, with larger deviations occurring only locally in areas of complex geometry or where the photographic material was of lower quality.

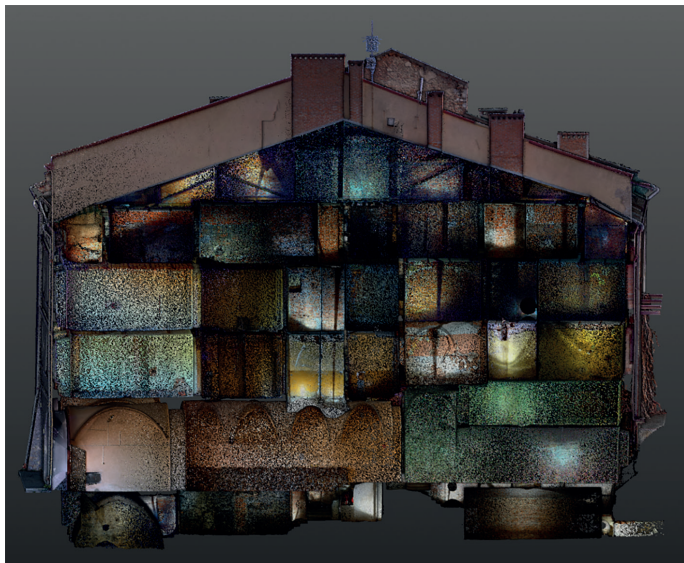


Source: Authors' own study

Fig. 6. Mesh model of the townhouse at the Market Square in Przemyśl (Rynek 11)

5.3. 3D model

A vector 3D model was developed in MicroStation on the basis of the point cloud. The modelling process involved representing building elements in accordance with the principles of orthogonality and geometric regularity typical of architectural objects. As a result, a model was obtained that enables faithful reconstruction of the building volume and façades as well as measurement of dimensions, geometric analyses and assessment of the technical condition of individual components. The average point cloud density of about 20 mm made it possible to capture minor façade features and essential structural elements, and the model may serve as a basis for further visualisations, renovation documentation, and integration with CAD and BIM systems.



Source: Authors' own study

Fig. 7. 3D vector model of the townhouse developed in MicroStation

5.4. Orthophotos

Orthophotos were generated for three main surfaces: the front façade, the rear façade and the roof. They were obtained by orthogonal projection of the textured mesh model onto suitably defined planes, while preserving the metric properties necessary for length and area measurements and for damage analysis without direct access to the object.

The front façade orthophoto had particularly high information value, enabling identification of architectural decorations, cracks in plaster, material losses and traces of previous repairs. The rear façade orthophoto provided data on parts of the building in poorer technical condition and with more limited observational accessibility. The roof orthophoto revealed the condition of the roofing, chimneys, flashing and drainage system, as well as elements invisible from ground level.

All orthophotos were equipped with a coordinate grid and a graphic scale and saved in formats suitable for use in GIS and CAD systems; comparison of characteristic dimensions measured on the orthophotos with those from the vector model and point cloud confirmed their high practical usefulness.



Source: Authors' own study

Fig. 8. Orthophoto of the front façade



Source: Authors' own study

Fig. 9. Orthophoto of the rear façade



Source: Authors' own study

Fig. 10. Orthophoto of the roof

6. Discussion

The results indicate that the adopted methodology effectively addresses the research objectives. Integration of terrestrial laser scanning with photogrammetry made it possible to obtain both a highly accurate geometric representation and rich visual information on the condition of the historic townhouse. In the context of cultural heritage documentation, this approach offers clear advantages over classical inventory methods, which are more time-consuming and less complete in terms of architectural details. The mean registration error below 1 mm is particularly important, as it implies that the spatial database can be used not only for visualisation but also for analyses requiring high geometric reliability. At the same time, such quality was achieved at the cost of considerable organisational effort in the field, a large number of stations and time-consuming data processing, which is a typical trade-off for documentation of historic objects with complex geometry and rich detail. Several factors contributed to the high accuracy of the final model. First, the dense network of tie points and evenly distributed GCPs ensured robust georeferencing and minimised systematic registration errors. Second, the use of a Trimble X9 scanner – characterised by a range noise of 0.3 mm at 10 m – provided inherently precise measurements under the prevailing conditions. Third, the overlap strategy between adjacent scan stations (minimum 30%) allowed redundant observations and facilitated automatic target-based registration with sub-millimetre closure errors. Fourth, consistent environmental conditions during the field campaign (overcast sky, low wind, stable temperature) reduced the effects of atmospheric refraction and target vibration. Fifth, the photogrammetric bundle adjustment benefited from high image overlap (80% forward, 70% side for façade flights) and the use of GCPs as constraints, which limited residual errors in the camera orientation to below 0.5 pixels. The synergistic effect of these factors – scanner precision, measurement redundancy, environmental stability and photogrammetric control – collectively produced the observed registration accuracy and geometric consistency of the integrated model.

In light of studies published in the international literature, the presented results are consistent with the observed trend in the development of 3D cultural heritage documentation [Rodriguez-Moreno et al. 2018, Tucci et al. 2017, Remondino and Campana 2014]. Papers emphasise that combining TLS and photogrammetry improves data completeness, enhances the quality of textured models and facilitates transition from measurement documentation to conservation and management analyses. Matsuoka et al. [2018] demonstrated that multi-sensor integration in urban historic environments reduces data gaps by up to 40% compared to single-sensor approaches, while Fassi et al. [2015] showed that the accuracy of integrated TLS-SfM models for façade documentation typically ranges from 0.5 to 2 mm RMS, which is consistent with the results presented in this study. The use of UAV platforms for complementing ground-level TLS data has also been confirmed as effective in comparable studies of historic urban buildings, especially for rooftop elements and upper façade zones where ground access is restricted [Remondino and Campana 2014, Tucci et al. 2017]. The

workflow adopted in the present study – from GCP placement through multi-sensor data acquisition to integrated mesh modelling and orthophoto generation – reflects the best-practice guidelines increasingly advocated in the field. Similarly, articles in *Geomatics*, *Landmanagement and Landscape* highlight the role of high-quality spatial data in documentation, planning and protection of spatial resources, including historically significant objects, and show that integration of TLS, ALS and UAV data improves the completeness of 3D models, while photogrammetric methods are effective when it comes to both documenting historic details and practical measurement tasks [Kwoczyńska et al. 2023, Kwoczyńska and Gudź 2023, Kłapa et al. 2023, Piech and Cieśla 2024].

The research also revealed limitations of the applied methodology, including partial inaccessibility of some façade fragments from ground level, dependence of texture quality on image acquisition conditions, large size of input datasets and the need to use advanced specialist software. These limitations do not undermine the value of the final results but rather indicate areas in which further development of procedures integrating TLS, UAV and 3D modelling may yield even better outcomes. In particular, the time investment in field data acquisition – spanning two full working days for scanning alone – and the post-processing burden of handling a 1.617-billion-point cloud represent practical constraints that should be considered when planning similar documentation projects. Future work could explore the use of mobile laser scanning to reduce field time, or the application of deep-learning-based point cloud segmentation tools to accelerate the cleaning and classification workflow. The methodology developed in this study is transferable to other historic townhouses in the Przemyśl market square and, more broadly, to densely built urban heritage environments where multi-sensor integration is necessary to achieve complete coverage and metrically reliable documentation.

7. Conclusions

The study confirmed that integrated use of terrestrial laser scanning and terrestrial and aerial photogrammetry is an effective method for producing detailed documentation of historic architectural objects. In direct response to the research objective, it can be stated that the 3D model of the townhouse at the Market Square in Przemyśl (Rynek 11), together with the point cloud, mesh model and orthophotos, constitutes a complete and useful dataset for architectural, design and conservation analyses. The most important outcomes include the point cloud comprising 1.617 billion points, the mean registration error below 1 mm, the development of a detailed mesh and 3D model and the generation of metric façade and roof orthophotos. These results confirm that modern geomatic technologies make it possible to create documentation of quality unattainable for traditional methods, and their use should be further developed particularly for historic objects threatened by degradation or undergoing revitalisation.

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