Assessing the Contribution of UAV and Terrestrial Laser Scanning to the Documentation of Immovable Cultural Heritage

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Abstract

Documentation of immovable cultural heritage is a fundamental prerequisite for its conservation, restoration, and sustainable management. Recent advances in geospatial technologies have significantly improved the accuracy, efficiency, and completeness of spatial data acquisition for historic structures. This study evaluates the contribution of terrestrial laser scanning (TLS) and close-range photogrammetry based on unmanned aerial vehicles (UAVs) to the engineering and architectural documentation of immovable cultural heritage. The Church of St. Petka (Sitovo village, Bulgaria), a 19th-century stone masonry monument, is used as a case study. High-density point clouds were generated using TLS and UAV-based photogrammetry and were georeferenced through classical surveying methods. The resulting datasets were assessed in terms of geometric accuracy, level of detail, and applicability for architectural documentation and conservation tasks. Accuracy evaluation based on measured control distances indicates a mean squared error below 1 cm for both methods. The results demonstrate that TLS provides superior precision and reliability for interior documentation, while UAV-based photogrammetry is particularly effective for capturing roof structures and inaccessible exterior elements. The integration of both technologies enables the creation of accurate 3D models and GIS-ready spatial products, supporting informed decision-making in cultural heritage conservation.

1. Introduction

Cultural heritage represents a fundamental component of historical memory and collective identity, encompassing tangible and intangible assets of historical, scientific, artistic, and social value. Among these assets, immovable cultural heritage, such as historic buildings, architectural ensembles, and urban structures, plays a particularly important role due to its spatial permanence and strong connection to the surrounding environment. The protection and sustainable management of such heritage require accurate, reliable, and up-to-date spatial documentation to support conservation, restoration, and long-term monitoring activities (Bedate et al., 2004; Pavlov, 1999; Kunchev, 2023; Kunchev, 2022; Kunchev, 2021).

Cultural heritage conservation is a process that consists of searching, studying, identification, documentation, registration, conservation, restoration and adaptation. Surveying and documenting the condition of architectural and built heritage is a pro-cess whose purpose is to describe the condition of the site and includes planning, in-formation about the ownership of the heritage site, describing the condition, risk assessment and making recommendations (Oncheva and Boshnakov, 2014). The documentation of immovable cultural heritage is a multidisciplinary process that involves identification, surveying, documentation, analysis, and interpretation of architectural and structural characteristics. Accurate spatial documentation is a prerequisite for informed decision-making in conservation practice and risk management, particularly in the context of aging structures and increasing environmental pressures (Bedate et al., 2004; Grussenmeyer et al., 2008; Kunchev, 2023). Traditional surveying methods have long been used to provide geometric control and verification however, they often face limitations when documenting complex geometries and inaccessible architectural elements.

In recent decades, advances in geomatics technologies have significantly trans-formed heritage documentation practices. Terrestrial laser scanning (TLS) and image-based photogrammetry enable the rapid acquisition of high-density three-dimensional (3D) spatial data, facilitating the creation of detailed geometric models and orthophotos for architectural documentation (Grussenmeyer et al., 2008; Remondino and El-Hakim, 2006; Fassi et al., 2013). Numerous studies have demonstrated the potential of TLS to provide accurate and complete representations of historic buildings, particularly for interior spaces and complex architectural elements (Pesci et al., 2013; Nocerino et al., 2014; Fregonese et al., 2017; Fidosova and Antova, 2021; Antova, 2022).

At the same time, UAV-based close-range photogrammetry has emerged as an efficient and flexible solution for documenting exterior facades, roof structures, and hard-to-reach areas of heritage sites. UAV platforms allow rapid data acquisition with high spatial coverage and visual realism, making them especially suitable for heritage environments characterized by limited accessibility (Nocerino et al., 2014; Kunchev, 2023). Comparative studies have shown that photogrammetric techniques can achieve accuracy levels comparable to TLS under appropriate acquisition and processing conditions (Murtiyoso et al., 2018; Tucci et al., 2017).

Despite the widespread adoption of these technologies, the selection and integration of appropriate surveying methods remain critical issues, particularly for small-scale heritage sites with complex geometry, mixed interior–exterior conditions, and challenging terrain. Previous research emphasizes that no single method can fully satisfy all documentation requirements, highlighting the need for integrated, multi-sensor approaches (Dore and Murphy, 2014; Brumana et al., 2018).

The main aim of this study is to evaluate the applicability and contribution of terrestrial laser scanning and UAV-based close-range photogrammetry, supported by classical surveying, for the documentation of immovable cultural heritage. Using the Church of St. Petka in Sitovo village, Bulgaria, as a case study, the research assesses the accuracy, completeness, and practical suitability of the applied methods and demonstrates their potential for generating reliable, GIS-ready spatial datasets to support cultural heritage conservation and management.

2. Materials and Methods

This section describes the study area, data acquisition techniques, control network, and data processing workflows applied in the documentation of the selected immovable cultural heritage site. The presented methodology is designed to ensure reproducibility

and to support further research based on the generated spatial datasets. No restrictions apply to the availability of the data used in this study, which are presented within the manuscript.

2.1 Study Area and Object Description

The study area is the Church of St. Petka, located in Sitovo village, Rodopi Municipality, Plovdiv Region, southern Bulgaria (Figure 1). The church was constructed in 1849 and represents a well-preserved example of 19th-century stone masonry religious architecture. It is situated on a rocky hill in the central part of the village, characterized by steep terrain and limited accessibility, which poses specific challenges for spatial data acquisition and documentation.



Figure 1. Church of St. Petka, Sitovo village, Bulgaria.

The church is a functioning religious building and is officially listed in the National Register of Cultural Properties as an immovable cultural heritage site of artistic and architectural value. Its cultural significance, combined with its complex geometry and constrained surroundings, makes it a suitable case study for evaluating modern surveying and documentation techniques.

The structure is built entirely of stone masonry, including the load-bearing walls and the roof. The roof consists of stone slabs arranged over a clay layer, a traditional construction technique typical for the region. The interior stone surfaces are plastered and decorated with original frescoes dating from the time of construction, which re-quire careful documentation due to their cultural and artistic importance.

From a geometric perspective, the building presents several challenges for spatial documentation. The irregular stone surfaces, the limited space surrounding the exterior walls, and the maximum interior height of approximately 7.8 m complicate the application of conventional surveying methods. These characteristics necessitate the use of advanced geomatics techniques capable of capturing both exterior and interior details with sufficient accuracy and completeness.

2.2 Control Network and Georeferencing

To ensure spatial consistency and accurate georeferencing of all datasets, a local control network was established in the study area. Existing geodetic control points located in the vicinity of Sitovo village were used as reference points, providing a stable link to the national coordinate framework. These points served as the basis for the extension of the control network around and inside the church.

In addition to the existing control points, new points were stabilized on the exterior facades and within the interior of the church. Permanent points on the exterior were fixed using marking nails, while temporary markers were placed inside the building due to conservation requirements. The spatial distribution of both existing and newly established control points is illustrated in Figure 2.

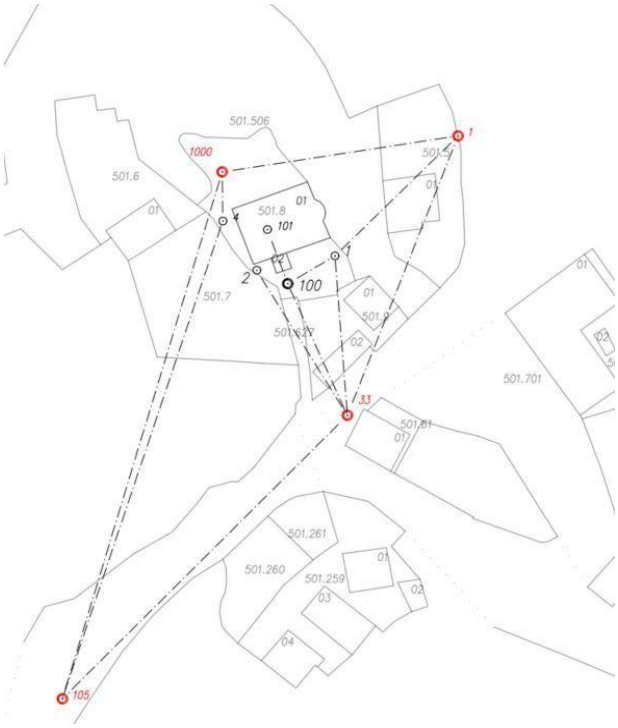


Figure 2. Spatial distribution of existing and newly established control points around and inside the Church of St. Petka.

All control points were measured using a Trimble S3 total station. The measurements provided three-dimensional coordinates (X-North, Y-East, H-Elevation) with high geometric accuracy, which served as a common reference framework for both terrestrial laser scanning and photogrammetric datasets. The control points ensured reliable transformation of the point clouds into a unified coordinate system and facilitated direct comparison between the different data acquisition methods.

The coordinates of the existing geodetic control points and the newly established points used for georeferencing are summarized in Table 1 and 2. These points were subsequently employed for the registration and transformation of point clouds, as well as for accuracy assessment through comparison with independently measured control distances.

№	North [m]	East [m]	Elevation [m]
pt1	4644036.48	426673.22	1272.91
pt33	4643981.94	426652.10	1273.07
pt105	4643926.64	426597.73	1271.39
1	4644013.05	426649.73	1276.68
2	4644010.26	426634.79	1275.69
4	4644019.87	426628.31	1275.66
100	4644007.65	426640.72	1275.67
101	4644018.203	426636.83	1275.96
102	4644020.56	426642.39	1275.98
103	4644021.22	426644.56	1276.06
1000	4644029.45	426628.21	1277.91

Table 1. Coordinates of the control points used for georeferencing.

№	m_x [mm]	m_y [mm]	m_h [mm]
pt1	25	18	-
pt33	27	27	-
pt105	28	28	-
1	3	3	1
2	4	4	2
4	4	4	2
100	4	5	2
101	6	8	2
102	7	9	3
103	8	10	3
1000	3	3	1

Table 2. Accuracy indicators of the control points used for georeferencing.

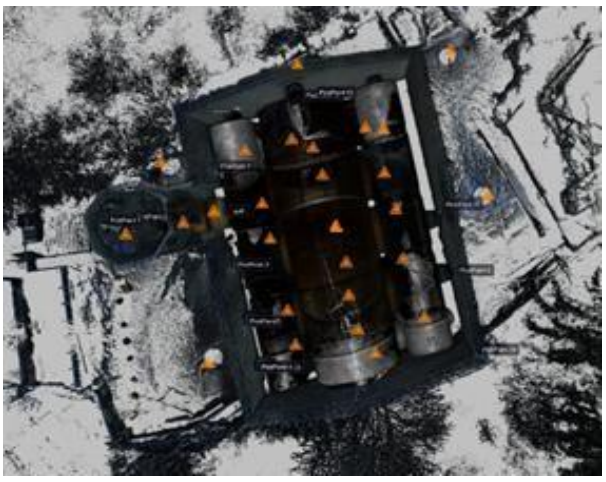
2.3 Terrestrial Laser Scanning

Laser scanners have a great advantage over other instruments because they record high-density data. The disadvantage of the method is that no fixed points from the deformable surface can be measured unless these points are specifically marked and their recognition is ensured (Ivanov, 2020; Nedyalkov, 2021).

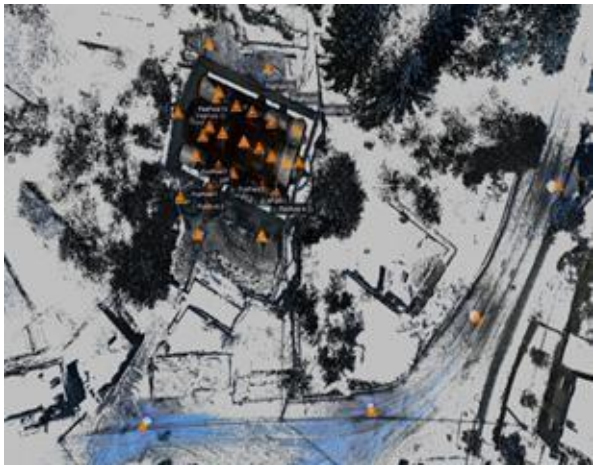
Terrestrial laser scanning was employed to acquire high-density three-dimensional spatial data of the Church of St. Petka, enabling detailed documentation of both exterior and interior architectural elements. The survey was carried out using a Trimble TX6 terrestrial laser scanner, which provides a full 360° horizontal and vertical field of view.

A total of 33 scanning stations were established to ensure complete spatial coverage of the structure. Of these, 20 stations were positioned inside the church, allowing detailed capture of interior geometry, including walls, arches, and ceiling elements. The spatial distribution of the interior scanning stations is shown in Figure 3a. The remaining stations were located around the exterior of the building to document the facades and roof geometry.

The specific topographic conditions of the site significantly influenced the scanning configuration. The church is situated on a steep rocky terrain, and the eastern facade is adjacent to a precipice, which restricted direct access. Consequently, four exterior scanning stations were positioned at distances ranging from 25 m to 34 m from the building in order to capture the eastern facade adequately. The locations of these exterior scanning stations are presented in Figure 3b.



a.)



b.)

Figure 3. Spatial distribution of interior and exterior terrestrial laser scanning stations: (a) interior stations; (b) exterior stations.

The selected scanning resolution was approximately 22.6 mm at a distance of 30 m, providing a dense point cloud suitable for detailed architectural documentation and subsequent geometric analysis. Terrestrial laser scanning was chosen as a primary data acquisition method due to its ability to capture complex geometries with high reliability and independence from lighting conditions, which is particularly advantageous for interior spaces.

2.4 UAV-Based Close-Range Photogrammetry

Close-range photogrammetric data were acquired using an unmanned aerial vehicle (UAV) DJI Mini 3. A free-flight mission was performed to capture overlapping images of the exterior facades and roof structure of the church. The flight configuration was adapted to the complex geometry of the building and the surrounding terrain. In total, 291 images were acquired for the exterior documentation. The spatial distribution of the captured images relative to the study site is illustrated in Figure 4.

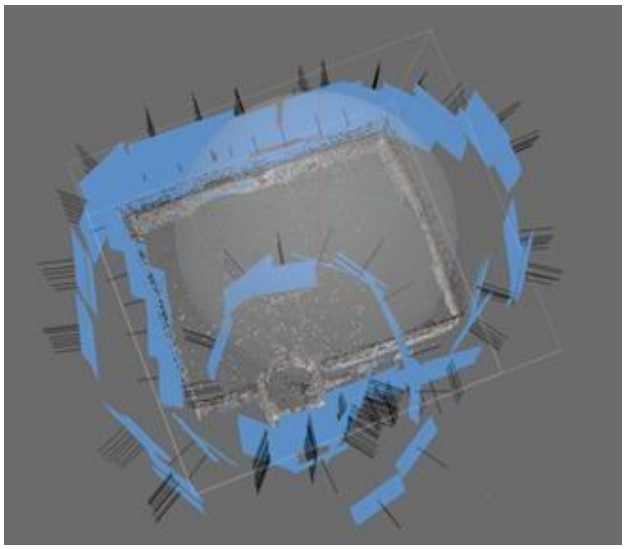


Figure 4. Spatial distribution of UAV and ground-based photographs used for photogrammetric data acquisition.

For the interior documentation, a combination of aerial and ground-based photographs was used in order to capture ceiling elements and upper wall sections. The maximum interior height

of the church is approximately 7.8 m, which necessitated the use of elevated image acquisition positions. Due to insufficient natural illumination inside the building, artificial floodlights were employed to improve lighting conditions and reduce image noise (Figure 5). A total of 1172 images were captured for the interior dataset.



Figure 5. Approximate interior height of the Church of St. Petka relevant for photogrammetric image acquisition.

2.5 Data Processing and Accuracy Assessment

The TLS data were processed using Trimble RealWorks software. Individual scans were registered by applying a combination of automatic surface matching and cloud-to-cloud registration methods. This approach was adopted due to limited overlap between certain scanning stations, caused by the complex terrain and restricted accessibility around parts of the building. The merged point cloud was subsequently georeferenced using well-distributed control points located on the exterior facades of the church. Noise filtering and the removal of extraneous objects were applied to improve the overall quality and usability of the dataset.

Photogrammetric images were processed using Agisoft Metashape software. Separate processing workflows were applied for the exterior and interior datasets in order to account for differences in acquisition geometry and lighting conditions. Control points measured with the total station were used for georeferencing. As a result, dense point clouds and orthophotomosaics of the facades were generated and exported for further architectural documentation and analysis.

The accuracy assessment was performed by comparing control distances measured using classical surveying methods with the corresponding distances extracted from the TLS and photogrammetric point clouds. For each control distance, the difference was computed as:

$$\delta S_i = S_{c,i} - S_{m,i} \quad (1)$$

where $S_{m,i}$ represents the distance measured by classical geodetic methods, $S_{c,i}$ is the corresponding distance derived from the point cloud, and δS_i is the difference for the *i*-the control distance.

The overall geometric accuracy of the datasets was evaluated using the root mean square error (RMSE), calculated as:

$$RMSE = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(\delta S_i)^2} \quad (2)$$

where n is the total number of control distances analysed. In addition, the mean value of the differences was computed to assess the presence of potential systematic errors:

$$\overline{\delta S} = \frac{1}{n-1}\sum_{i-1}^{n}\delta S_i \quad (3)$$

and the standard deviation was calculated to evaluate the dispersion of random errors:

$$\sigma = \sqrt{\frac{1}{n-1}\sum_{i-1}^{n}\left(\delta S_i - \overline{\delta S}\right)^2} \quad (4)$$

This statistical analysis enabled an objective assessment of the geometric reliability of the TLS and photogrammetric datasets and provided a basis for their comparative evaluation.

No generative artificial intelligence (GenAI) tools were used in the design of the study, data acquisition, data processing, or interpretation of results. All analyses were conducted using established surveying and photogrammetric software.

3. Results

This section presents the results obtained from terrestrial laser scanning and UAV-based close-range photogrammetry, as well as the outcomes of the accuracy assessment based on control distance comparisons. The results are presented objectively, without interpretation, which is provided in the subsequent Discussion section.

3.1 Terrestrial Laser Scanning Results

The terrestrial laser scanning survey resulted in a high-density point cloud representing both the exterior and interior geometry of the Church of St. Petka. The initial merged point cloud contained approximately 948 million points, which was reduced to 785 million points after noise filtering and removal of extraneous objects.

The exterior point cloud provides a detailed geometric representation of the facades, roof geometry, and surrounding terrain (Figure 6). Architectural elements such as wall irregularities, roof stone slabs, and facade details are clearly distinguishable. The interior point cloud captures walls, arches, and ceiling elements with high completeness and continuity (Figure 7), allowing for the extraction of sections, profiles, and architectural layouts.



Figure 6. TLS-derived point cloud of the exterior of the Church of St. Petka.

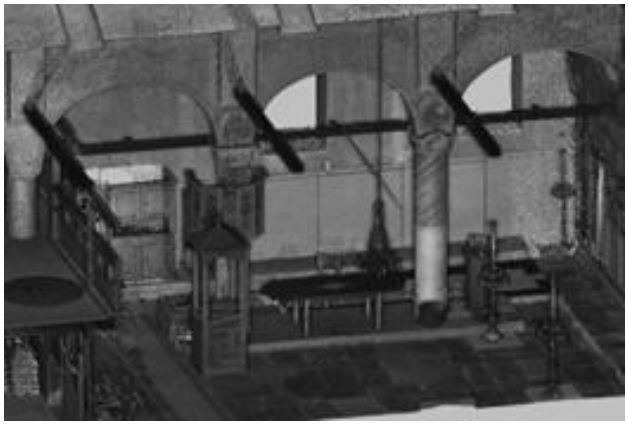


Figure 7. TLS-derived point cloud of the interior of the Church of St. Petka.

3.2 UAV-Based Photogrammetry Results

Photogrammetric processing of the UAV and ground-based images resulted in a dense point cloud with a total of approximately 506 million points. The dataset exhibits high visual realism due to the availability of colour and texture information derived from the images (Figure 8).



Figure 8. Point cloud obtained from UAV-based close-range photogrammetry.

The photogrammetric point cloud provides detailed representation of exterior facades and roof elements, including areas that were difficult to access using ground-based methods. Based on this dataset, orthophotomosaics of the facades were generated, enabling accurate architectural documentation and visual inspection of surface details (Figure 9).



Figure 9. Orthophotomosaic of the south facade of the Church of St. Petka.

3.3 Accuracy Assessment Results

The accuracy assessment was based on the comparison of 52 control distances, measured independently using classical surveying methods and extracted from the TLS and photogrammetric point clouds. The merged point clouds used for the comparison are illustrated in Figure 10, where the datasets obtained by the two methods are distinguished by colour.

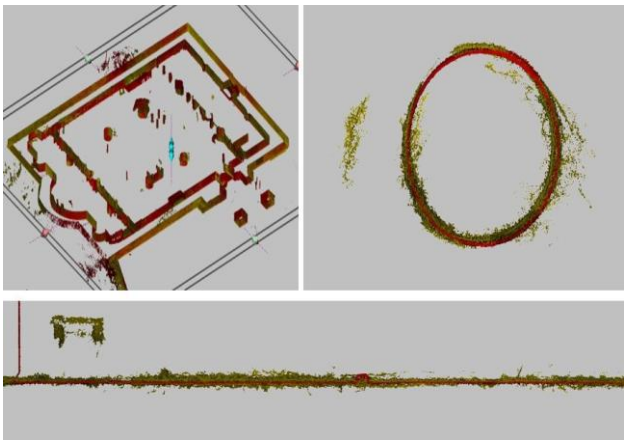


Figure 10. Cross-section of merged TLS and photogrammetric point clouds used for accuracy assessment (yellow—UAV-based photogrammetry; red—TLS).

The differences between measured and computed distances were evaluated using the statistical indicators described in Section 2.5. The root mean square error (RMSE) values obtained for the analysed datasets were below 1 cm, indicating a high level of geometric consistency between the classical measurements and the distances derived from the point clouds. The distribution of the RMSE values for the examined distance series is presented in Figure 11. The results demonstrate that both terrestrial laser scanning and photogrammetric methods meet the accuracy requirements for the documentation of immovable cultural heritage.

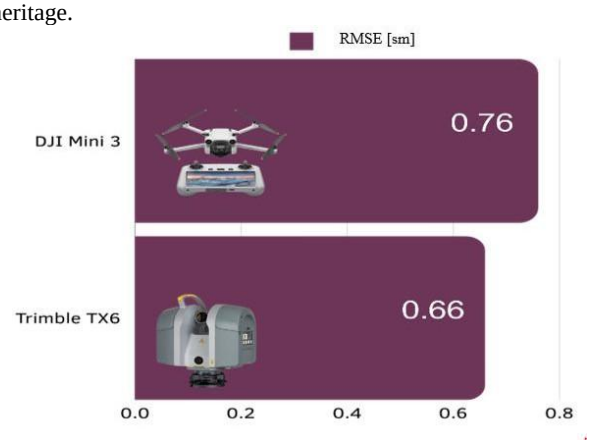


Figure 11. RMSE values in cm derived from the comparison of control distances for the Church of St. Petka.

4. Discussion

This section discusses the results obtained from the application of TLS and UAV-based close-range photogrammetry for the documentation of immovable cultural heritage. The discussion focuses on the comparative performance of the applied methods,

the achieved geometric reliability, and their suitability for typical heritage documentation tasks.

4.1 Comparison of Terrestrial Laser Scanning and UAV-Based Photogrammetry

The results confirm the complementary nature of terrestrial laser scanning and UAV-based photogrammetry when applied to historic masonry buildings. TLS demonstrated high geometric completeness and consistency, particularly for interior spaces, where limited lighting conditions and restricted manoeuvrability often constrain image-based approaches. This finding is consistent with previous studies that identify TLS as a reliable method for capturing complex interior geometries and architectural details (Remondino et al., 2014; Lerma et al., 2010; Barazzetti et al., 2010; Guidi et al., 2014; Murtiyoso et al., 2018). In contrast, UAV-based photogrammetry proved especially effective for documenting exterior facades and roof structures, including areas that are difficult or unsafe to access using ground-based surveying techniques. The flexibility of UAV image acquisition allows efficient coverage of elevated architectural elements, while the resulting textured models and orthophotomosaics provide high visual realism, which is valuable for architectural documentation and conservation planning (Nex and Remondino, 2014; Remondino et al., 2014).
The site-specific conditions of the Church of St. Petka, including steep terrain and restricted access to certain facades, further highlight the advantages of an integrated, multi-sensor approach. Similar conclusions have been reported in heritage documentation studies emphasizing that combining TLS and photogrammetry improves data completeness and operational efficiency (Dore and Murphy, 2014).

4.2 Accuracy and Suitability for Heritage Documentation

The conducted accuracy assessment demonstrated that both TLS and UAV-based photogrammetry achieve geometric consistency compatible with the requirements for immovable cultural heritage documentation. The achieved accuracy levels are comparable to those reported in similar studies involving historic masonry structures and complex architectural environments (Nocerino et al., 2014; Murtiyoso et al., 2018; Fregonese et al., 2017).
While TLS exhibited higher robustness in interior environments due to its independence from lighting conditions, photogrammetric accuracy was more sensitive to image quality, illumination, and acquisition geometry. Nevertheless, when sufficient overlap and appropriate lighting conditions were ensured, photogrammetry produced results suitable for facade documentation and surface analysis. These observations are consistent with previous findings highlighting the importance of acquisition strategy in image-based heritage documentation (Grussenmeyer et al., 2011).

4.3 Applicability of Geomatics Methods for Immovable Cultural Heritage Documentation

Based on the obtained results, a comparative evaluation of the applicability of the selected surveying methods was performed. The suitability of classical surveying, UAV-based photogrammetry, and TLS for common documentation tasks related to immovable cultural heritage is summarized in Table 3. The comparison indicates that TLS provides the highest versatility across most documentation tasks, particularly those requiring detailed geometric analysis, interior coverage, and the extraction of sections and profiles. UAV-based photogrammetry is most advantageous for roof and exterior documentation, offering efficient access to elevated and hard-to-reach areas, while classical surveying remains essential for control measurements, verification of results, and deformation-related tasks. These findings support previous research emphasizing that integrated geomatics workflows offer the most reliable and comprehensive solutions for heritage documentation (Stylianidis and Remondino, 2016; Chiabrando et al., 2016)].

Documentation task	Classical surveying	UAV-based photogrammetry	Terrestrial laser scanning
Verification of output data	CC	N	N
Georeferencing	CC	CC	CC
Topographic plan	Y	CC	Y
Documentation of facades	CC	CC	Y
Roof documentation	CC	Y	CC
Documentation of exterior deformations	Y	N	Y
Architectural layouts	CC	CC	Y
Sections and profiles	CC	N	Y
Documentation of interior deformations	Y	CC	Y

Table 3. Applicability of selected surveying methods for documenting immovable cultural heritage (Y – applicable; N – not applicable; CC – applicable under certain conditions).

4.4 Limitations and Future Perspectives

Despite the positive results, certain limitations were identified. Interior photogrammetric documentation required additional artificial lighting, while TLS data acquisition was constrained by limited accessibility around specific exterior facades. Future research may focus on the integration of the generated 3D datasets into GIS and HBIM environments, enabling advanced spatial analysis, long-term monitoring, and change detection of immovable cultural heritage sites (Ilieva, 2022; Pavlov, 1999; Stylianidis and Remondino, 2016; Chiabrando et al., 2016).

5. Conclusions

This study evaluated the contribution of TLS and UAV-based close-range photogrammetry, supported by classical surveying, to the documentation of immovable cultural heritage through a case study of the Church of St. Petka in Sitovo village, Bulgaria. The applied multi-method approach enabled the acquisition of accurate, consistent, and detailed three-dimensional spatial data suitable for architectural documentation and conservation-related analyses.
The results demonstrated that TLS provides the most comprehensive and reliable geometric information, particularly for interior spaces, architectural layouts, and the extraction of sections and profiles, due to its high point density and

independence from lighting conditions. UAV-based photogrammetry proved to be especially effective for the documentation of exterior facades and roof structures, offering efficient access to elevated and hard-to-reach areas and producing visually realistic models and orthophotomosaics. Classical surveying remains indispensable for control measurements, verification of results, and deformation-related tasks, ensuring geometric consistency across all datasets.

The accuracy assessment confirmed that the applied methods achieve sub-centimeter geometric consistency relative to classical surveying measurements, fulfilling commonly accepted accuracy requirements for the documentation of immovable cultural heritage. The comparative analysis further highlighted that no single method can independently satisfy all documentation needs, and that the integration of TLS, UAV-based photogrammetry, and classical surveying provides the most robust and versatile solution.

The findings of this study support the use of integrated geomatics methodologies for cultural heritage documentation and underline their potential for generating GIS-ready spatial datasets that can support conservation planning, management, and future monitoring. Future research may focus on the integration of the generated 3D models into GIS and HBIM environments, as well as on the application of the proposed approach for long-term change detection and risk assessment of heritage sites.

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