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COMPARATIVE ANALYSIS OF ALS, TLS AND UAV TECHNOLOGIES FOR 3D BUILDING MODELING AND DIGITAL TWIN GENERATION

Selin KESKİN^{1*}

Jan KANUK²

Arzu ERENER¹

¹ Department of Geomatics, Engineering Faculty, Kocaeli University, Kocaeli, 41000, Türkiye.

² Institute of Geography, Faculty of Sciences, P.J.Šafárik University in Košice, Slovakia, Jesenna 5, 040 01 Košice PHOTO-MAP, s.r.o., Poludníková 3/1453, 040 12 Košice.

* Corresponding Author: S. Keskin, ✉ slnkskn59@gmail.com  0009-0004-2464-4086

ABSTRACT

This study provides a comprehensive comparison of airborne laser scanning (ALS), terrestrial laser scanning (TLS), and unmanned aerial vehicle (UAV) technologies for acquiring 3D data on building geometries, emphasizing their applications in geographic information systems (GIS) and 3D modeling. Using the Faculty of Science building at Pavol Jozef Šafárik University in Košice as a test site, the performance of these methods was evaluated based on key parameters, including point cloud density, data acquisition time, and model quality.

ALS is a valuable tool for topographic mapping, offering efficient data acquisition over large areas, but it faces significant limitations in capturing detailed vertical features. TLS proved to be the most accurate method, delivering high-density point clouds for complex architectural details, though at the expense of extended acquisition times and limited applicability for large-scale areas. UAVs provided a versatile and efficient alternative, particularly excelling in capturing roof details, but encountered challenges in resolving vertical structures and complying with regulatory constraints.

The findings highlight the complementary nature of these technologies. Integrating the precision of TLS with the aerial flexibility of UAVs can overcome individual limitations, significantly enhancing 3D modeling capabilities. This synergy offers substantial potential for applications in urban planning, architectural documentation and supporting digital transformation initiatives within the framework of digital twin concepts.

Keywords: Airborne Laser Scanners, Terrestrial Laser Scanners, Unmanned Aerial Vehicle, Geographic Information Systems, Point Cloud.

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INTRODUCTION

3D Photogrammetry is a sophisticated technique used to calculate the 3D coordinates of objects in real space by analyzing images captured from various positions. This method involves superimposing images taken from multiple viewpoints to create a comprehensive representation of the object (Triggs et al., 2000; Remondino et al., 2009; Westoby et al., 2012). In the context of remote sensing, 3D object detection refers to the process of identifying and localizing objects in a three-dimensional space using data collected from remote sensing platforms. Geographic Information System (GIS) is a system that integrates functions such as collecting, storing, analyzing, and presenting spatial data (Aranof, 2005). GIS facilitates the visualization of information on maps and 3D scenes by organizing data into layers and enabling spatial analysis (Lillesand, and Kiefer, 2000). In today's rapidly evolving landscape of GIS and mapping technologies, the integration of remote sensing and imaging systems has transformed how we perceive and analyze spatial data (Longley et al., 2015; Shan & Toth, 2018).

The detection and classification of buildings are critical tasks in urban planning, disaster management, and environmental monitoring. Traditional methods, such as manual mapping, are time-consuming and prone to errors, prompting the developing of more efficient technologies like Unmanned Aerial Vehicles (UAVs), Terrestrial Laser Scanners (TLS), and Airborne Laser Scanners (ALS). These technologies enable more accurate, automated, and scalable solutions for detecting buildings in urban areas while providing rich datasets for object detection and modeling. However, each system has distinct advantages, limitations, and operational considerations.

UAVs are versatile tools used for capturing high-resolution imagery and 3D data in areas that are otherwise hard to access, making them invaluable for environmental monitoring and disaster response (Colomina & Molina, 2014; Burdziakowski, 2018; Shan & Toth, 2018; Salach et al., 2018). These lightweight and flexible platforms can carry various sensors, such as RGB, multispectral, hyperspectral or thermal cameras, LiDAR systems, to capture detail imagery and three-dimensional data (Ahmed et al., 2022). Despite their advantages, UAVs are limited by short battery life, dependence on favorable weather, and regulatory restrictions, particularly in urban or areas and areas close-to airports.

TLS, on the other hand, offers ground-based, high-resolution scanning, ideal for detailed mapping of architectural structures and terrains. (Vosselman & Maas, 2010). This technology provides high-accuracy 3D data for building modeling and inspections but is constrained by the need for stable set-ups, extended scan times, and limitations related to line-of-sight and environmental factors, such as weather, obstructions.

ALS is a widely used airborne technology for large-scale mapping, capable of capturing data over extensive areas with high efficiency (Baltsavias, 1999). It is typically used to capture large-scale topographic data from airborne platforms, providing dense point clouds that can be used for building detection over vast areas. However, it is less detailed than TLS for small-scale applications, has high

operational costs due to the use of aircraft, and is limited by factors such as cloud cover or obstacles like tall trees.

Various factors, such as data acquisition efficiency, processing speed, cost-effectiveness, and environmental impact, must be carefully evaluated to determine the most suitable solution for a specific application (Goodchild & Li, 2012; Liu et al., 2017). Accordingly, this study aims to conduct a comprehensive comparative analysis of ALS, TLS, and UAVs in the context of GIS applications, emphasizing their respective advantages, limitations, and potential for synergistic integration. Upon reviewing the existing studies, it was found that while numerous studies have addressed UAV (citations), ALS (citations), and TLS (citations) technologies individually in the context of object detection, there is a notable lack of research comparing these three technologies simultaneously for building detection performance. Although various criteria were considered in these studies, the factors analyzed were predominantly consistent across most of the reviewed research (Girardeau-Montaut et al., 2005). These criteria include the elevation of the acquired data, data quality, and point cloud density. Data that fall outside these criteria are typically derived using a general-to-specific approach. Studies indicate that the relative importance of these features and their classification into suitability categories vary based on research objectives, expert opinions, or national regulations. Peterson et al. (2019) demonstrated the effectiveness of UAV imagery in calculating plane slopes and estimating the vertical geometry of non-uniform surfaces. Similarly, Sugiura and Takahashi (2015) explored TLS and UAV photogrammetry for capturing building façades, highlighting the trade-offs between data accuracy and operational efficiency. Kaufmann and Steidl (2017) conducted a comparative analysis of ALS, TLS, and UAV technologies, assessing their accuracy and efficiency in generating 3D point clouds for urban modelling across diverse contexts. Sayar (2022), in his master's thesis, investigated the use of TLS and UAV data in cultural heritage conservation, employing aerial photogrammetry to document areas inaccessible to terrestrial laser scanning. Saritaş et al. (2023) utilized terrestrial laser scanning in their study but recommended the inclusion of drones after observing limitations in capturing roof details. Cheung et al. (2017) compared TLS and UAV technologies in forested areas, concluding that integrating drones with TLS offers an effective alternative to manual methods. Collectively, these studies underscore the strengths and limitations of each technology in specific applications, while emphasizing their potential for complementary use.

Scientific studies emphasize the unique strengths and limitations of each technology across various application areas. Consequently, comparing and integrating ALS, TLS, and UAV technologies is essential to identifying the most suitable solution for specific applications. This study aims to evaluate the relative advantages of these technologies by analyzing key factors, including point cloud density, data acquisition time, 3D model quality, device battery life, and other relevant variables. The building of the Faculty of Science at Pavol Josef Šafárik University in Košice, Slovakia was selected as the test site for this comprehensive evaluation.

1. DATA AND METHODS

For the comparison of the individual methods, the Faculty of Science building of Pavol Jozef Šafárik University in Košice (Figure 1) was selected for several reasons. Geographically, it is located at a latitude of 48.729326 and a longitude of 21.24867. Pavol Jozef Šafárik University, established in 1959 as the second classical university in Slovakia, is housed in a former monastery, which holds historical and architectural significance. The building is a two-story structure featuring classical artistic elements and two inner atriums. Its complex architectural details present a challenge for accurate data collection and the creation of a 3D digital model.

Later, a new standalone building with a cuboid shape and a steel-reinforced concrete structure was added to the historic structure. This modern addition is connected to the historic building by an elevated corridor. The complex shape and construction of this building provide highly suitable conditions for testing and comparing the performance of ALS, TLS, and UAV technologies in creating a digital 3D model of the building.

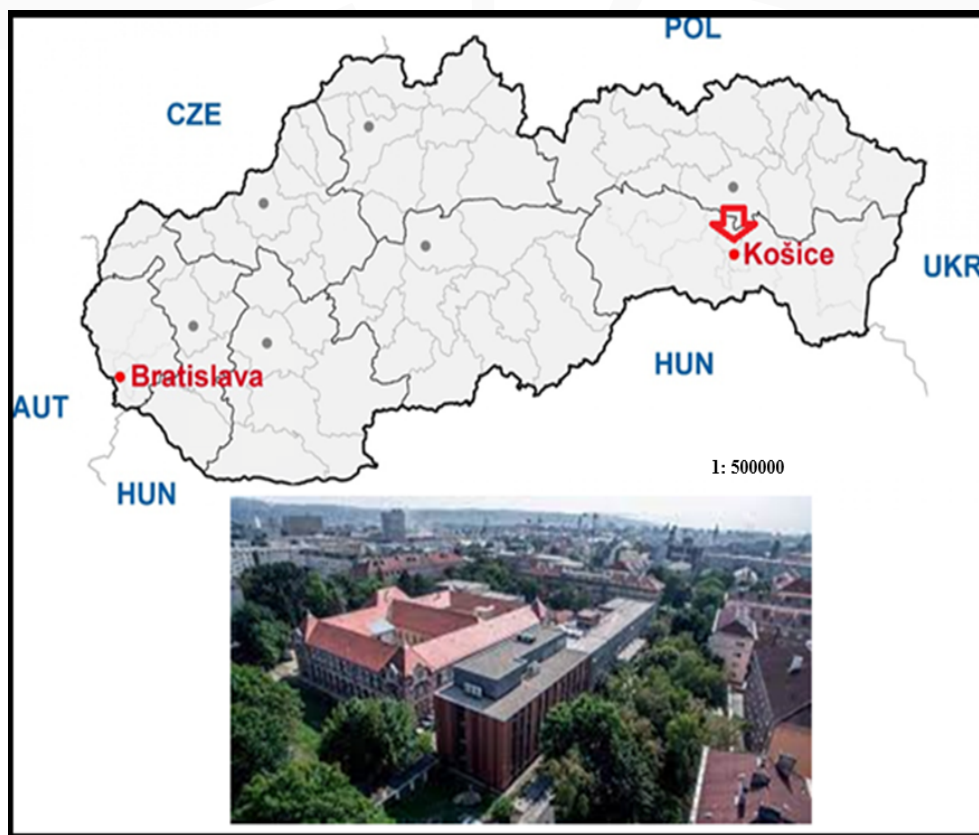


Figure 1. Building of Faculty of Science, Pavol Joseph Šafarik University in Košice, Slovakia

The comparison focuses on the processes of 3D data acquisition and processing, as well as subsequent analyses, as outlined in the conceptual framework illustrated in Figure 2.

The comparison of the individual technologies is based on selected parameters, such as the number and density of points, data collection time requirements, processing demands, and the ability to create a detailed 3D model. The conceptual framework of the methodological procedure is illustrated in Figure 2. This figure offers an overview of the distinct steps involved for each technology and summarizes the activities carried out at each stage.

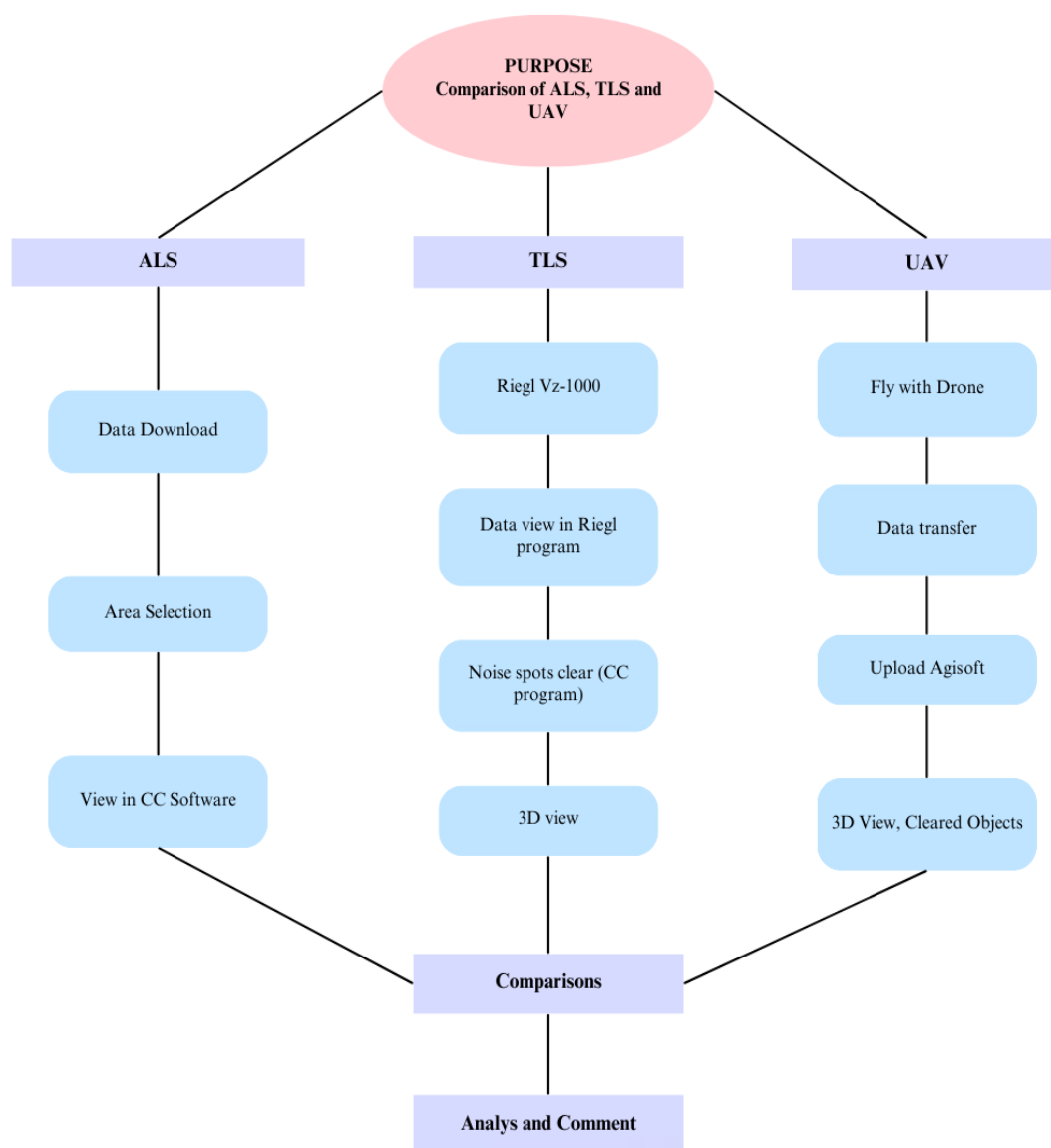


Figure 2. Flow chart used when comparing ALS, TLS and UAV technologies

The ALS belongs to the category of active remote sensing methods, utilising LiDAR technology (Light Detection and Ranging). ALS can be categorised based on the platform or carrier on which the laser system is mounted into two groups: (i) piloted and (ii) unmanned aerial platforms.

Piloted platforms, such as aeroplanes, are typically designed for large-scale mapping of extensive areas (at the regional or national level). These platforms operate at higher speeds and altitudes, which generally results in lower point densities (20–30 points/m²). Conversely, unmanned aerial systems, often multicopter, can fly at lower altitudes, just a few dozen metres above the terrain, and at slower speeds. This enables them to produce higher point densities, sometimes exceeding 200 points/m². However, unmanned platforms are suited for smaller areas, typically up to 2–3 km². For this study, point clouds obtained from ALS conducted with a laser system mounted on a piloted aircraft were used. The point clouds were sourced from the Slovak mapping platform ZB GIS, managed by the Geodesy, Cartography, and Cadastre Authority of Slovakia. Slovakia is widely recognised as a leader within the European Union in terms of accessibility to airborne laser scanning data. The platform can be accessed at <https://zbgis.skgeodesy.sk>. The ALS data used in this study was pre-processed and prepared for 3D modelling. Specifically, classified point clouds corresponding to Class 2 (ground) and Class 5 (building) were utilised.

TLS also employs LiDAR technology. A critical input parameter for ALS data is the flight trajectory, recorded during the flight using an IMU (Inertial Measurement Unit) combined with GNSS. After calculating the flight trajectory, the returns coordinates recorded by the LiDAR system are determined based on GPS timestamps. In the case of TLS, the coordinate computation for points is referenced to the origin of the coordinate system at each scanning position, typically the scanner's location. Individual scans are then aligned to form a complete point cloud representing the surveyed object. This stationary scanning approach, where the scanner is placed on a fixed platform, allows for higher accuracy in the resulting point clouds. TLS devices were originally developed for modelling architectural and engineering structures but have since been adapted for high-resolution mapping of terrains (such as quarries and glaciers), vegetation (e.g., forests), and other landscape features within limited distances, typically ranging from 50 to 300 metres (Sayar, 2022).

In this study, the terrestrial laser scanner Riegl VZ-1000 (Figure 3) was utilised. This device is equipped with a laser transmitter and receiver, a motorised mirror scanning mechanism, 32 GB of flash memory for data storage, an integrated GPS receiver (L1) with an antenna, dual-axis inclination sensors, a built-in laser plummet, and a digital compass.



Figure3. Riegl Vz-1000

During the scanning process, a total of 18 scanning positions were established, each spaced within 20 meters around the Faculty of Science building. The placement of these positions was carefully planned to ensure sufficient overlap between scans. Subsequently, a two-step registration process was performed using the RiSCAN Pro software. In the first step, manual registration was carried out based on four identical points. These points were selected to be easily identifiable across overlapping scanning positions and to ensure they were neither collinear nor coplanar. Stable points, such as sharp edges of windows, cornices, roof elements, traffic signs, and similar features, were prioritized. In the second step, automatic registration was performed using a multi station adjustment algorithm based on the planes derived from plane patch filter tool. The final registration accuracy of the individual point clouds reached 0.015 meters. For exporting the resulting point cloud, points from all scanning positions were merged into a single file and exported in the *.las format.

An UAV, commonly referred to as a drone, is a remotely controlled aircraft without an onboard pilot. UAVs can be classified into various categories based on factors such as maximum take-off weight, range, engine type, and design. A significant advantage of UAVs in mapping is their ability to carry a variety of sensors, including cameras, laser scanners, and sensors capable of capturing different parts of the electromagnetic spectrum. They can also perform flights following pre-programmed flight trajectories. In our study, we used a DJI Phantom 4 Pro UAV equipped with a 20MP CMOS camera and a three-axis gimbal for camera stabilization. The flight was planned and executed using the Ground Station Pro application, where a polygon defining the area of interest was outlined. The desired ground

sampling distance (GSD) was set to 0.015 meters, along with the required lateral and front overlaps between individual image footprints. The application then calculated the flight altitude, flight line plan, and speed. Approximately 257 nadir-oriented images, orthogonal to the Earth's surface, were captured during the flight. After take-off, the camera settings were manually adjusted to match the lighting conditions, ensuring radiometric consistency across the captured images. The flight duration was 30 minutes (Figure 4). Following the flight, the captured images were processed using the Agisoft Metashape software.



Figure 4. DJI Phantom 4 Pro V2.0

2. DATA ANALYSIS AND RESULTS

Table 1 presents the formats and sizes of the initial files obtained from each method. The smallest file sizes were observed for data collected using ALS. The file size indirectly reflects the density of the point cloud, which, compared to the other methods, is relatively low. In contrast, TLS data showed the largest file sizes among the three techniques, providing the highest point density.

When examining the processed versions of these files, changes in both file format and size were observed. The analysis revealed a reduction in file size for each dataset. This reduction is attributed to the removal of areas outside the building that are irrelevant to the study.

Regarding file formats, both TLS and UAV datasets underwent format changes. The TLS data were saved in a new format to facilitate processing. The .psx format used for these data retains the normal of individual points, which is an important intermediate step in creating a 3D model of buildings.

Table1. Information of Files

	Time	ALS	TLS	UAV
File Format	Before Analysis	.las	.las	JPG
File Format	After Analysis	.las	.txt	.psx
File Size	Before Analysis	44 MB	8.36 GB	3.10 GB
File Size	After Analysis	13.1 MB	2.26 GB	668 MB

The analysis of point cloud data collected using ALS, TLS, and UAV technologies (Figure 5) revealed distinct advantages and limitations for each method in capturing surfaces and processing 3D spatial coordinates to create 3D building models. Among the three methods, ALS data exhibited the lowest point density. This limitation, particularly evident on vertical surfaces such as building walls, prevents the creation of a complete and detailed 3D building model. While ALS is highly effective for topographic mapping of large areas, it is less suitable for representing intricate architectural features.

In contrast, TLS data achieved the highest point density, making it the most accurate and reliable method for capturing complex architectural details. Features such as window frames, cornices, and roof structures were accurately documented, showcasing the precision of this technology. However, TLS was less effective for roof details due to its ground-based perspective, which leaves portions of the roof obscured from view. Furthermore, TLS is the least time-efficient method, requiring careful device setup, detailed scanning plans, and significant effort in data processing, particularly for complex structures.

UAV technology offers a balanced solution, providing sufficient point density and superior visualisation of 3D models through integrated RGB colouring. By capturing data from the air, UAVs effectively map roof areas that are challenging for ground-based systems. However, their ability to capture perpendicular walls and building facades in detail is limited. Additionally, UAV mapping is less effective in shaded or obstructed areas, such as parts of buildings covered by trees. Challenges related to battery life and compliance with flight regulations, especially in controlled airspaces, also need to be managed when using UAVs for building mapping.

A comparison of the resulting 3D models highlights the strengths and limitations of each method. TLS produced the most precise results for intricate architectural details, while UAVs excelled in capturing roof data and providing comprehensive visual representations. Although ALS had the lowest resolution, it was highly effective for large-scale geographic coverage. Integrating these technologies has the potential to overcome their individual limitations, combining the precision of TLS with the

efficiency and aerial coverage of UAVs to create detailed and comprehensive 3D representations. This synergy could be invaluable in applications such as architectural documentation, urban planning, and environmental monitoring.

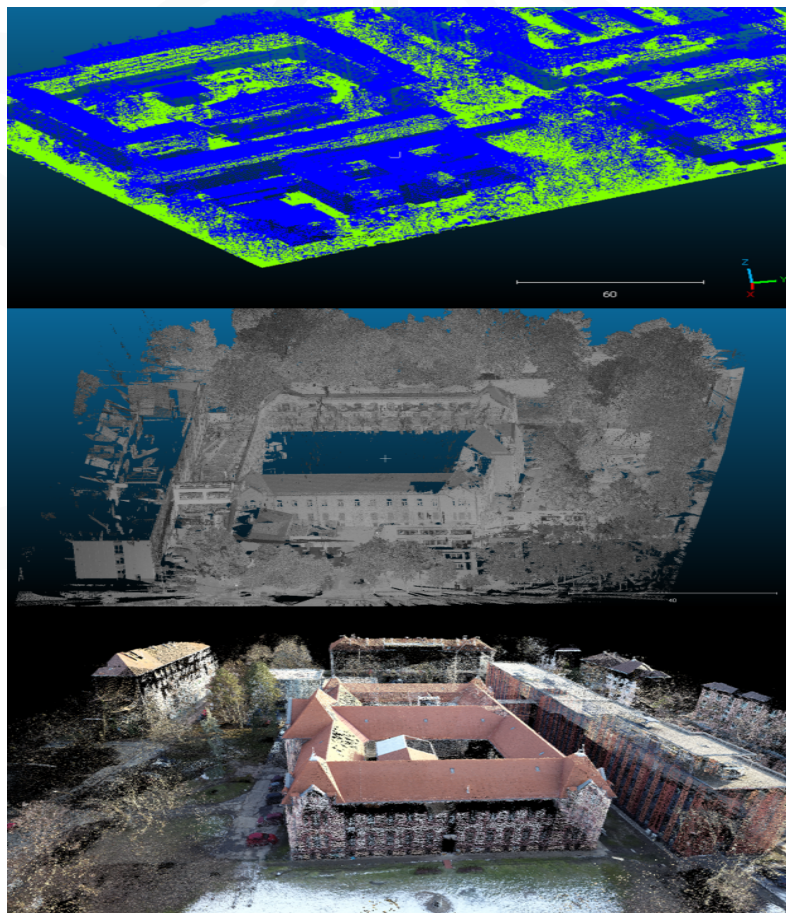


Figure 5. Oblique view of triple comparison (top: ALS, middle: TLS, below: UAV)

The creation of 3D building models was performed using the open-source software CloudCompare, employing the Poisson Surface Reconstruction tool. The resulting 3D models were subsequently analysed and compared.

The ALS data proved unsuitable for generating detailed 3D building models due to an insufficient number of points on surfaces such as building facades. This lack of density prevents the spline function in the Poisson Surface Reconstruction tool from accurately estimating the surface, leading to the generation of artificial surfaces.

For creating 3D building models, UAV data demonstrated the best results in terms of colouring and visual appeal (Figure 6). However, upon closer inspection, small objects only a few centimetres in size were lost or overly generalised. From this perspective, TLS data offers significantly more accurate

results. For example, when examining the lower parts of the building, reflections of parked cars were visible in the TLS data, while this issue did not occur in the UAV data. This highlights a key advantage of UAVs—there is no need to remove vehicles for effective scanning.

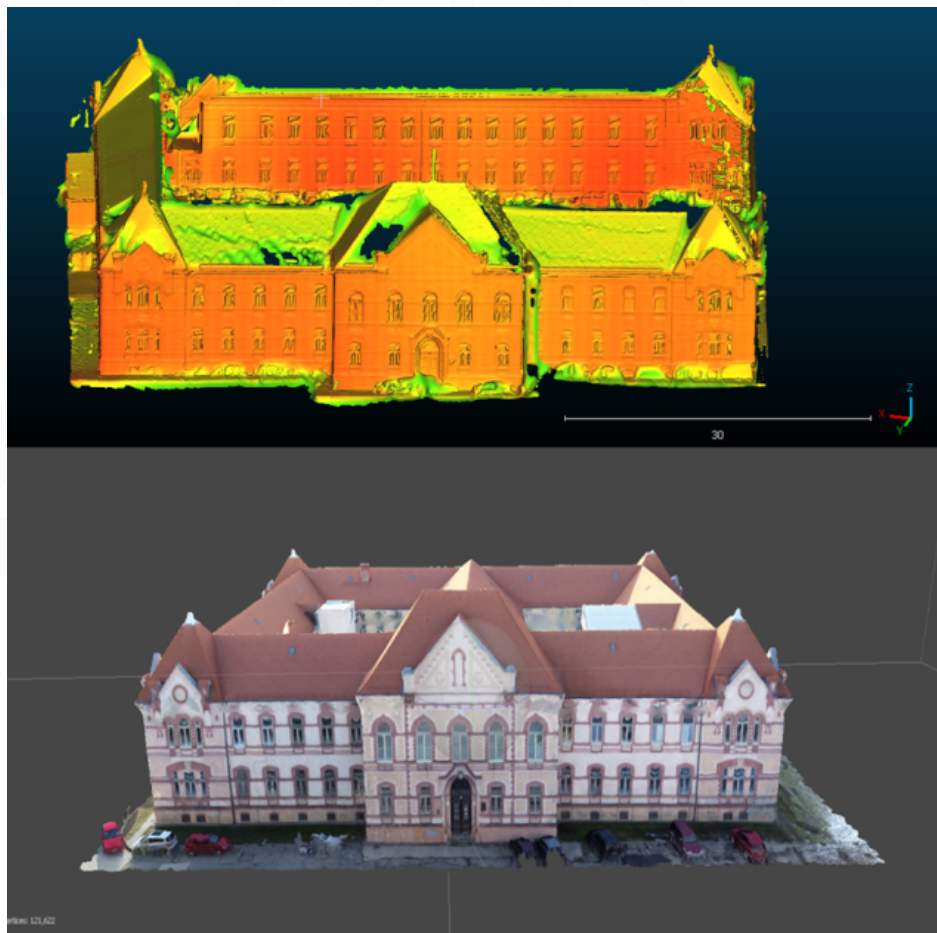


Figure 6. TLS (top) and UAV frontview (below)

When viewed obliquely, roof data captured by TLS appeared less detailed compared to UAV data, which provided clearer and more complete roof representations. Conversely, under-roof areas were better captured by TLS but were poorly represented in UAV data. This difference arises from the distinct perspectives of the technologies: TLS scans upward from the ground, while UAVs capture surfaces from an aerial top-down view.

A comparison of the three technologies is summarised in Table 2, based on six key criteria. TLS offers the highest point density, which is critical for capturing intricate architectural details, particularly for building facades and structural elements. UAVs provide moderate point density, sufficient for roof mapping and photogrammetry, while ALS data has the lowest density, especially when capturing vertical features such as walls.

TLS captures the largest number of points, enabling the creation of highly detailed and accurate models. UAVs, although capturing fewer points, are effective for roof scanning and producing visually appealing models. ALS, on the other hand, is limited to pre-existing data from online repositories and does not support direct 3D modelling in this context. However, it remains useful for generating spatial data for broader geographic applications.

Table 2. Comparison of ALS, TLS, UAV

	ALS (Archive data)	TLS	UAV
Density	TLS > UAV > ALS		
Number of Points	432850	251807788	1000000
Time	30 mins	3 hours	1 hour
3D	-	+	+
Weight	-	9.8 kg	1388 gr
Battery life	-	5 hours	30 mins

The challenges associated with TLS include the weight of the equipment, which affects portability and ease of deployment. UAVs, being lightweight and easily transportable, offer significant advantages in this regard. ALS, as archive data, does not involve equipment deployment, making it incomparable in this respect. Battery life also plays a crucial role in data collection. UAVs have the shortest operational duration, with a typical battery life of just 30 minutes, which can limit data acquisition in larger areas. TLS, by contrast, offers up to 5 hours of battery life, making it more suitable for extensive scanning projects.

CONCLUSION

This study examines and compares three methods ALS, TLS and UAV for acquiring 3D data on building geometries with the aim of supporting 3D building modelling. The growing accessibility of modern technologies like laser scanning and photogrammetry has increasingly replaced traditional surveying techniques such as tachymetry and levelling. However, this shift has introduced new challenges, particularly in the context of digital transformation and the need for standardized procedures for 3D geospatial data acquisition and processing, especially for the concept of building digital twins. Addressing the question of which technology delivers results that meet the evolving requirements for high-quality 3D building models is central to this research.

Among the compared methods, TLS stands out as the most precise, capable of capturing highly detailed point clouds of building structures. It enables the accurate documentation of architectural

elements, including their positions and dimensions, making it an indispensable tool for construction, restoration, and architectural modifications. Its ability to provide dense and detailed data extends beyond building structures to include surrounding features such as vegetation, fences, and railings. Despite its advantages, TLS is limited in its ability to map roofs or areas of buildings obscured from ground view. Additionally, the time required for data collection and processing renders it less suitable for large-area surveys. In urban environments, the method faces challenges from noise introduced by moving objects such as pedestrians and vehicles, further complicating the data-cleaning process.

UAV technology offers an alternative to TLS with its rapid deployment and automated generation of 3D models. UAVs have established their utility across a range of applications, including surveying, construction monitoring, and logistics tracking. The method simplifies the operational process, requiring minimal effort to define areas of interest and configure image capture parameters. However, UAVs are highly dependent on favourable weather conditions, such as adequate lighting and low wind, to ensure effective data collection. They also face regulatory constraints, including the need for operator certification and compliance with flight rules. While UAVs can capture roof details efficiently, issues with vertical structures in point cloud generation can arise, although these can often be mitigated through oblique imaging techniques.

ALS, on the other hand, is notable for its availability in Slovakia and its utility in generating large-scale overviews. Its datasets, often freely accessible, make ALS a preferred choice for acquiring general geometric data about buildings. However, its lower spatial resolution compared to TLS and UAV limits its effectiveness for detailed 3D modelling. While the point density on roofs is adequate for generating basic 3D models, the lack of detail on vertical structures poses significant constraints for more intricate reconstructions.

The choice of technology ultimately depends on the specific needs of a project, as each method has distinct strengths and limitations. TLS excels in delivering highly detailed and precise data, UAVs are optimal for flexibility and rapid data collection, and ALS is ideal for large-scale mapping with readily available datasets. Looking forward, integrating these technologies to combine their strengths holds significant potential for advancing the standardization and accuracy of 3D building modelling workflows.

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