

# Synergy of UAV Aerial Survey Methods and LiDAR Scanning for the Study of Planar Objects of Historical and Cultural Heritage

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## Abstract

*The combination of UAV aerial surveys and LiDAR scanning provides high resolution, accuracy, and data comprehensiveness, which are critical for creating detailed digital models and maps. The aim of the work was to create an orthophotomap and an accurate digital surface model of the research area using a synergy of UAV aerial imagery and airborne LiDAR scanning with laser scanners from two different manufacturers. Aerial surveying with UAVs and aerial LiDAR scanning using two scanners, DJI Zenmuse L2 and CHCNAV Alpha Air 450, was conducted for the territory of the historical and cultural reserve "Ancient Zvenyhorod" in Ukraine, which was chosen as the research object. Based on UAV aerial survey data, an orthophotomap of the study area was created at a scale of 1:2000. Additionally, point clouds of the reserve's surface were generated from the aerial survey data and compared with point clouds obtained from LiDAR scanning. It was determined that, since the object's territory covers 26.8 hectares, the aerial survey was conducted from a height of 145 meters in one flight, while the laser scanning of the territory was carried out at a height of 60 meters to better capture the elements of the area. The scanning operations were automatically divided into two scans with UAV landings for battery replacement. The object's territory located at the junctions of the automatically divided scans lacked point cloud information for both scanners. It was proposed to supplement the LiDAR scanning point cloud with points generated from the aerial survey in the area where they were missing. Before copying the point cloud for the area lacking LiDAR data, an analysis and height alignment of points between the LiDAR data and aerial survey were performed. As a result of the research, an accurate digital surface model of the historical and cultural reserve was constructed, containing all elements of its territory.*

**Keywords:** Aerial Survey, Cloud Point, Cultural Heritage, LIDAR, UAV

## 1. Introduction

In today's world, technology is advancing at an extraordinary pace, allowing its application in various fields of science and culture. One of the areas where new technologies play a significant role is archaeology and the study of historical and cultural objects. The use of unmanned aerial vehicles (UAVs) with aerial photography and LiDAR scanning has become a true breakthrough in this field.

These methods allow for the acquisition of highly accurate data about objects without the need for physical intervention, which is especially important for preserving fragile and valuable artifacts. They provide fast and detailed analysis, contributing to a deeper understanding and preservation of historical and cultural values.

The relevance of using UAVs and LiDAR scanning in the study of planar objects of historical and cultural heritage cannot be overstated. The preservation of such objects is an important task that requires precise and reliable research methods. Traditional methods are often associated with the risk of damaging the objects and can be quite labor-intensive and time-consuming. In this context, modern technologies such as UAV aerial photography and LiDAR scanning become indispensable tools. They allow for the creation of highly accurate three-dimensional models of objects, which significantly facilitates their study, analysis, and restoration. Such models enable scientists to examine the structure and condition of objects in detail, uncover hidden details, and develop effective preservation strategies.

Furthermore, the combination of these technologies opens up new possibilities for integrating various data sources, promoting a more comprehensive approach to studying historical and cultural heritage. This not only aids in the preservation of objects but also allows for more accurate reconstruction of historical events and contexts in which these objects existed. Therefore, the implementation of UAVs and LiDAR scanning in archaeological research is not only relevant but also essential for preserving our cultural heritage for future generations. The aim of the work was to create an orthophotomap and an accurate digital surface model of the research area using a synergy of UAV aerial imagery and airborne LiDAR scanning with laser scanners from two different manufacturers.

## 2. Analysis of Previous Research

The integration of UAVs equipped with cameras and LiDAR technology for heritage mound inspection creates highly detailed surface models by leveraging the UAV's ability to capture extensive, high-resolution aerial imagery combined with LiDAR's precise three-dimensional topographic data. This synergy ensures comprehensive coverage and accurate representation of the mound's surface features, crucial for effective preservation and analysis. Combining terrestrial laser scanning (TLS) and UAV photogrammetry for Heritage Building Information Modeling (HBIM), as demonstrated in the case study of Tarsus St. Paul Church, offers a robust approach to documenting historical structures, where TLS provides high-precision data on intricate details, and UAV photogrammetry captures the overall structure and context. Using UAVs to monitor Native Hawaiian coastal cultural heritage sites significantly enhances resilience against natural and human-induced threats, enabling frequent, cost-effective, and non-intrusive surveys that capture

high-resolution images and generate accurate digital models of the coastal landscape. Prior calculation of the accuracy of monitoring cultural heritage objects using UAVs and laser scanning is essential for evaluating the expected precision and reliability of data, ensuring that generated models and maps meet the required standards for heritage conservation [1][2][3] and [4].

However, there are several limitations to these studies. UAV flights and LiDAR scans can be affected by weather conditions, potentially limiting data collection. The integration of different datasets can introduce complexities in data processing and alignment, leading to potential inaccuracies. High costs associated with advanced equipment and software may limit accessibility for some researchers. Additionally, the need for specialized skills to operate UAVs, LiDAR systems, and data processing tools can be a barrier to widespread adoption. Finally, regulatory restrictions on UAV flights in certain areas may pose challenges to comprehensive data collection in all desired locations [5][6][7] and [8].

The use of unmanned aerial vehicles (UAVs) for three-dimensional documentation of historical and cultural heritage significantly enhances the ability to collect detailed data and create accurate models. Critical factors and guidelines for 3D surveying and modeling in cultural heritage include measurement accuracy, technology compatibility, and proper equipment calibration. The convergence of terrestrial laser scanning (TLS) and UAV photogrammetry enables the creation of highly accurate 3D documents of cultural heritage objects, as demonstrated in studies creating complex polyhedral building models by integrating stereo-aerial imagery and LiDAR data. However, these studies have certain limitations: weather conditions can affect UAV flights and LiDAR scans, the integration of different datasets can complicate processing and alignment, high costs of equipment and software may limit accessibility for some researchers, the need for specialized skills can be a barrier to widespread adoption, and regulatory restrictions on UAV flights may pose challenges for comprehensive data collection [9][10][11][12][13][14][15] and [16].

The smart merging method for hybrid point cloud data using UAV and LiDAR in earthwork construction enhances the accuracy and efficiency of topographic surveys by combining the strengths of both technologies. Using linear regression and lines intersecting to extract punctual entities in a LiDAR point cloud refines data analysis and feature extraction.

The combined use of terrestrial laser scanning and UAV photogrammetry in mapping alpine terrain offers comprehensive and high-resolution topographic data, essential for studying challenging landscapes. Automated registration of potential locations for solar energy production using LiDAR and small format photogrammetry optimizes site analysis and planning, leveraging precise elevation and surface data for better decision-making [17][18] [19][20][21] and [22].

The AHP-based method for selecting the best 3D scanner for cultural heritage applications provides a systematic approach to evaluating different scanning technologies, ensuring that the chosen equipment meets specific needs for heritage conservation. Similarly, 3D modeling using videogrammetry and laser scanners offers valuable tools for reverse engineering, enabling detailed reconstruction of objects. The development of semi-automatic, low-cost 3D laser scanning systems for reverse engineering democratizes access to advanced scanning technologies, though it may sacrifice some precision and reliability. High-precision 3D scanning techniques for measuring coral surfaces highlight the method's minimal invasiveness and reproducibility, but might be limited by the specific biological context and environmental conditions. The assessment of 3D documentation techniques in archaeology aims to standardize best practices for intra-site data recording, yet may face challenges in balancing detail with practical fieldwork constraints. Finally, surveying and modeling of rock discontinuities using terrestrial laser scanning and photogrammetry with semi-automatic approaches enhances efficiency in linear outcrop inspection, although it may struggle with the complexity of geological features and potential data integration issues [23][24][25][26][27][28] and [29].

Limitations of these studies include potential inaccuracies in lower-cost systems compared to high-end models, challenges in achieving consistent results across different environmental and contextual conditions, and the need for advanced expertise in handling complex data processing and integration tasks. Additionally, the semi-automatic nature of some approaches might introduce errors or reduce the level of detail captured. Automatic fusion of photogrammetric imagery and laser scanner point clouds streamlines the integration of data from different sources, improving efficiency in creating detailed 3D models. Despite its advantages, the automatic fusion process can introduce errors if the alignment and calibration of data sources are not meticulously managed, potentially compromising the

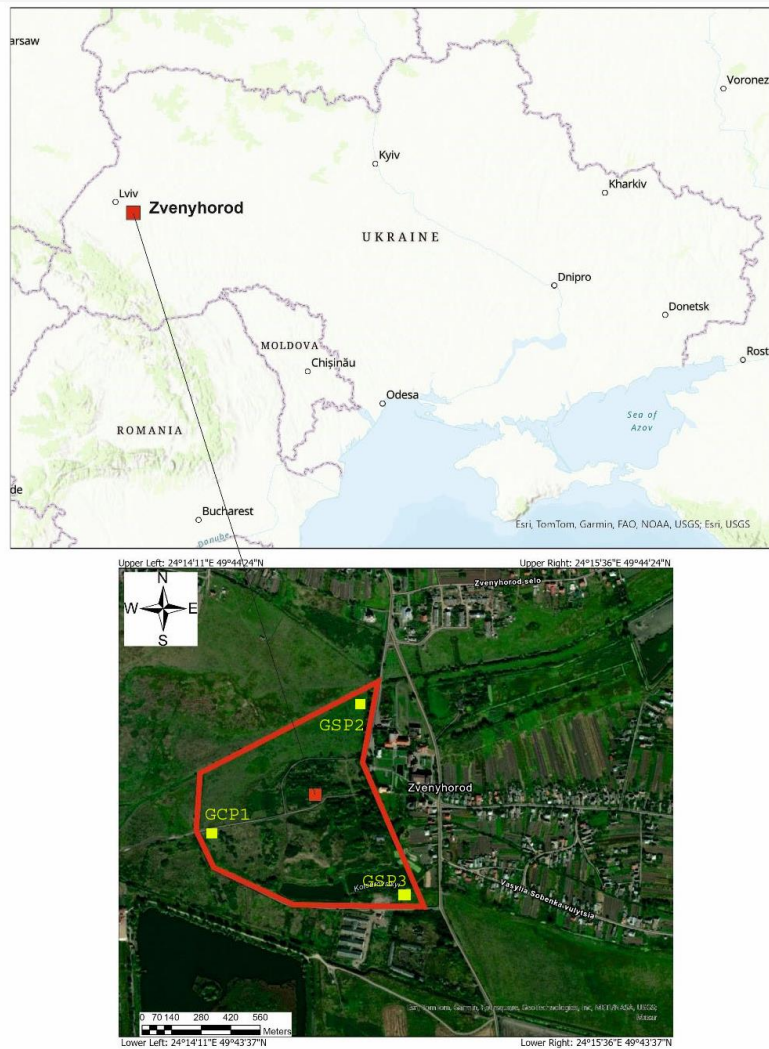
precision of the resulting models [30][31][32] and [33]. The fusion of laser scanning data, maps, and aerial photographs for building documentation enhances the accuracy and contextual understanding of architectural features. This approach provides a rich dataset for detailed modeling, but may encounter difficulties in harmonizing data from different sources, which can lead to inconsistencies or gaps in the final documentation.

3D modeling of Sidon Sea Castle using a combination of terrestrial laser scanning and photogrammetry offers a robust method for capturing the castle's structural details and historical significance. While this approach yields high-quality models, it may be limited by the need for precise data integration and potential challenges in capturing complex architectural features accurately. Limitations of these studies include potential issues with data alignment and integration, which can affect the accuracy of the final models. The complexity of managing and processing large datasets from multiple sources can introduce errors if not handled carefully. Additionally, the reliance on automated processes may lead to inaccuracies if the systems are not perfectly calibrated or if there are discrepancies between different types of data.

### 3. Study Area

Zvenyhorod hillfort is an archaeological complex located near the village of Zvenyhorod in the Lviv region of Ukraine. This site comprises the remnants of the ancient Rus' city of Zvenyhorod, which was one of the important administrative and trade centers of the Halych-Volhynia state in the 10th–13th centuries. Figure 1 shows the schematic layout of the research object with marked GCP. Zvenyhorod was founded in the early 10th century as a fortress to protect against nomads and neighboring principalities. It became one of the centers of political and economic life in the region due to its strategic location at the intersection of trade routes.

In the 11th century, the city became the capital of a separate principality known as the Zvenyhorod Principality. During this time, the city was actively developed: new fortifications, churches, residential, and administrative buildings appeared. One of the most famous princes of Zvenyhorod was Prince Volodymyrko Volodarevich, who founded the dynasty of Halych princes. Throughout the 12th century, Zvenyhorod maintained active trade relations with other Rus' cities, as well as with countries in Central Europe. Archaeological findings indicate a high level of craft development, including pottery, metallurgy, and jewelry making.



**Figure 1:** Zvenyhorod hillfort in Zvenyhorod near Lviv city with marked GCP

However, in the 13th century, the city suffered destruction during the Mongol-Tatar invasion. Zvenyhorod lost its significance as a political center and gradually transformed into a small settlement. Today, Zvenyhorod hillfort is an important archaeological monument. Excavations are conducted on the site, resulting in numerous artifacts that provide insight into the life and culture of the ancient Rus' city. There is also a museum where visitors can learn about the history and findings of this unique place (Figure 2).

#### 4. Methods and Materials

To achieve the objective of the work, it is necessary to:

- ✓ Perform aerial photography with the DJI Matrice UAV using the DJI Zenmuse P1 aerial camera.

- ✓ Perform LiDAR surveying with the UAV using two laser scanners.

Two DJI quadcopters, namely the Matrice 300 RTK and the Matrice 350 RTK, were used for the surveying tasks (Figure 3). The Leica GS16 receiver, installed 2 meters from the UAV takeoff and landing site, was used as the base station. PPK (Post-Processed Kinematic) technology was utilized for communication, providing geolocation accuracy at the  $\pm 2\text{-}5$  cm level. Aerial photography was carried out using the DJI Zenmuse P1 camera (Figure 4), which was available to the expedition. The DJI Zenmuse P1 is designed for high-precision photogrammetric work and is widely used for creating 3D models, mapping, agricultural monitoring, infrastructure inspection, and other applications requiring high accuracy and image quality [34].



**Figure 2:** Aerial view of Zvenyhorod Hillfort



**Figure 3:** DJI quadcopters



**Figure 4:** DJI Zenmuse P1 digital aerial camera mounted on the UAV gimbal

The aerial photography was conducted to create an orthophotomap and build a Digital Terrain Model (DTM) of the object's territory. The orthophotomap is planned to be created at a cartographic scale of 1:2000. To create an orthophotomap at a cartographic scale of 1:2000 using a UAV, an a priori accuracy assessment must be calculated, taking into account the accuracy requirements for this scale. A scale of 1:2000 means that 1 cm on the map corresponds to 20 m on the ground. For the 1:2000 scale, the planimetric accuracy usually should be within  $\pm 0.2$  m (20 cm). This means that the allowable coordinate deviation on the ground should not exceed 20 cm. For the 1:2000 scale, the vertical accuracy usually should be within  $\pm 0.5$  m. To ensure compliance with accuracy requirements, we determine the optimal flight altitude. For the applied camera, the sensor pixel size is 4.4  $\mu\text{m}$ , and the focal length is 35 mm. We need to achieve a Ground Sample Distance (GSD) that provides the necessary accuracy. For creating an orthophotomap at a 1:2000 scale, it is recommended to use a GSD of 2-3 cm per pixel. The formula for calculating GSD (Equation 1):

$$GSD = \frac{H \cdot S_w}{P_w \cdot F}$$

Equation 1

Where  $H$  is the flight altitude (in mm),  $S_w$  is sensor width (mm),  $P_w$  is number of pixels in sensor width (pixel), and  $F$  is the focal length (mm). During the experiment, the flight altitude was 145 meters. Therefore, GSD calculated using equation 1 is 1.82 cm/pixel.

Thus, one pixel on the image corresponds to 1.82 cm on the ground, which aligns with a scale of 1:2000. The calculation shows that to create an orthophotomap at a scale of 1:2000, a GSD of 2 cm/pixel must be ensured, and high-precision geolocation systems should be used. Meeting these conditions will achieve the necessary planimetric and vertical accuracy, in line with cartographic standards [35]. For designing aerial photography, it is necessary to calculate the longitudinal and transverse overlaps, as well as other quantitative and qualitative image characteristics. Therefore, we proceed to calculate the required longitudinal and transverse overlaps, depending on the elevation difference in the area, using formulas (Equation 2 and 3):

$$P_x(\%) = p + \frac{h}{H-h}(100-p)$$

Equation 2

$$P_y(\%) = q + \frac{h}{H-h}(100-q)$$

Equation 3

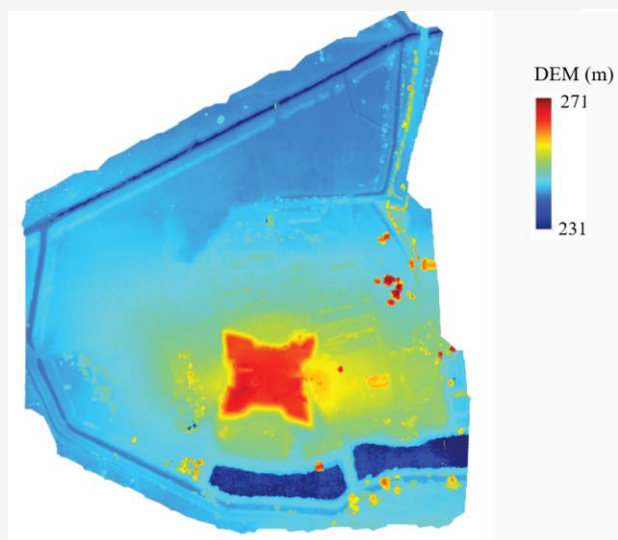
Where  $P_x$  and  $P_y$  represent the percentage of longitudinal and transverse overlap, respectively.  $h$

represents the current flight height of the UAV above ground level.  $H$  represents a reference height (a fixed height or altitude);  $p$  is the specified longitudinal overlap of the aerial images;  $q$  is the specified transverse overlap of the aerial images.

During the aerial survey, the longitudinal overlap was set at 60% and the transverse overlap at 40%. Over the area of the historical and cultural reserve, covering 26.8 hectares, 458 images were taken. The orthophotomap was created using the 6-degree Gauss-Krüger projection, coordinate system – USK 2000, zone 5. The orthophotomap was created using DJI Terra, which offers an intuitive interface and powerful tools for generating high-quality orthophotomaps. After uploading the ground control points and images, and aligning them, a point cloud was generated before creating the elevation map [36] and [37].

At intermediate stages of creating the orthophotomap, a scene overlap map was created, showing the overall overlap zone (both longitudinal and transverse) of all the images, as well as a digital surface model (Figure 5). The final stage involved generating the orthophotomap of the reserve based on the created dense point cloud (Figure 6). Coordinates of 10 control points were measured on the orthophotomap, and an assessment of spatial coordinate accuracy was conducted. The control points were selected as contours on the terrain, with their coordinates measured using a South S82 GNSS receiver in RTK mode. The points were chosen geometrically evenly across the entire surface of the object. The results are presented in Table 1. To calculate the RMS errors of the 10 control points, we first compute the mean values, and then calculate the Root Mean Square (RMS) errors [38].

The RMS errors were:  $m_x = 0.056$  cm.  $m_y = 0.050$  cm., and  $m_z = 0.115$  cm. As shown in the table 1. the RMSEs do not exceed the allowable values, meeting the requirements for a 1:2000 topographic map. LiDAR surveying of the historical and cultural reserve "Ancient Zvenyhorod" was conducted using two scanners from different manufacturers with varying characteristics, to compare the results with each other and with the DTM constructed from the aerial imagery data. The scanners used were the DJI Zenmuse L2 (Figure 7(a)) and the CHCNAV Alpha Air 450 (Figure 7(b)). The LiDAR scanning process was divided into two blocks for each scanner, with the possibility of battery replacement. The scanning height for each LiDAR system was 60 meters above the ground, with an average flight speed of 4.45 m/s, a pulse frequency of 240 kHz, and a scanning rate of 720 kHz. The planned scanning area for each scanner was covered by 14 flight paths (Figure 8).



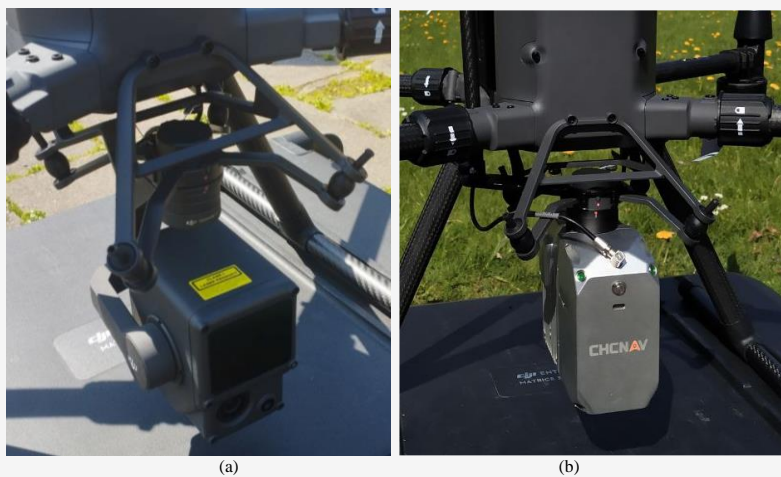
**Figure 5:** DSM of the historical and cultural reserve "Ancient Zvenyhorod"



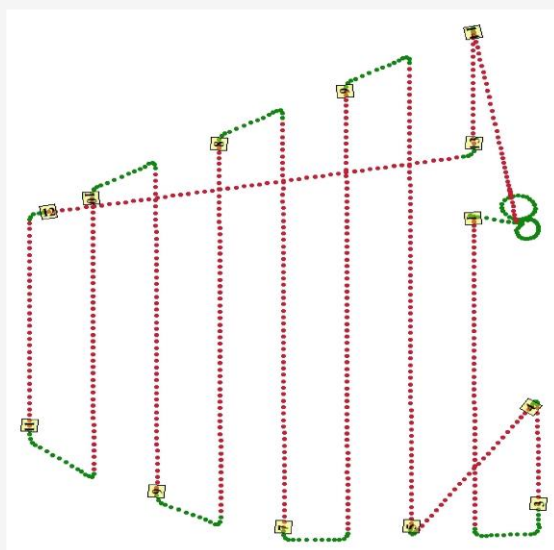
**Figure 6:** Orthophotomap of the historical and cultural reserve "Ancient Zvenyhorod"

**Table 1:** Accuracy assessment of the constructed orthophotomap

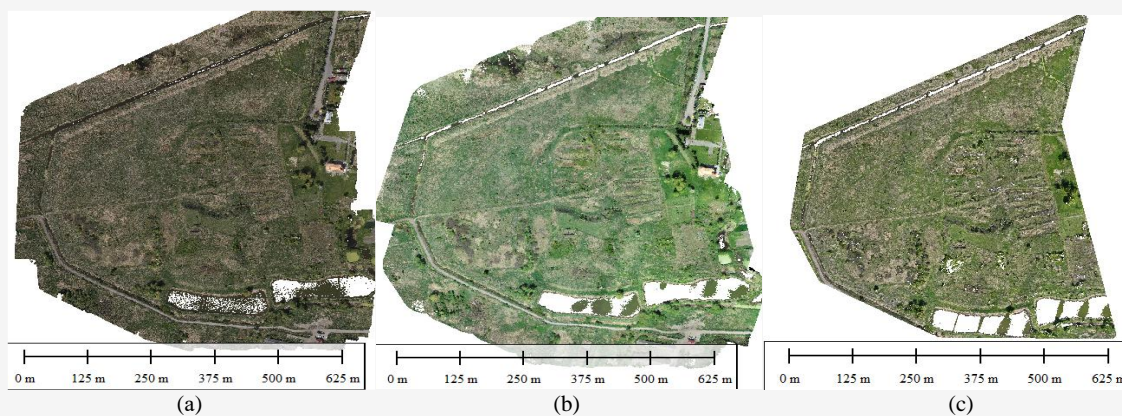
N	$\Delta X$ (m)	$\Delta Y$ (m)	$\Delta Z$ (m)
1	0.037	0.067	-0.048
2	-0.012	0.052	0.046
3	-0.084	0.075	-0.030
4	0.022	-0.007	0.019
5	0.011	-0.085	0.026
6	0.091	0.028	0.035
7	-0.019	-0.011	0.045
8	0.009	-0.058	0.031
9	-0.087	0.006	-0.038
10	-0.099	0.017	-0.078



**Figure 7:** Airborne laser scanners:  
(a) DJI Zenmuse L2 and (b) CHCNAV Alpha Air 450



**Figure 8:** Flight paths for airborne laser scanning



**Figure 9:** Point clouds constructed from the data:  
(a) UAV aerial imagery; (b) LiDAR data from the UAV using the CHCNAV Alpha Air 450 scanner;  
(c) LiDAR data from the UAV using the DJI Zenmuse L2 scanner

Processing LiDAR data from the DJI P2 UAV LiDAR system in Terra Scan is a complex process. Terra Scan provides functions for processing LiDAR data, such as noise filtering, segmentation, and point classification. Using the processed LiDAR data, Digital Terrain Models (DTM) and Digital Surface Models (DSM) are generated for analysis and use in further applications. As with the aerial imaging, a 6-degree Gauss-Krüger projection and the UTM 2000 coordinate system, zone 5, were used for LiDAR scanning. To improve accuracy, three ground control points along the edges of the study area, captured using GNSS measurements, were used. This was done for the data obtained from both scanners. Figure 9 shows the point clouds constructed from the LiDAR data of the two scanners and the UAV aerial imagery.

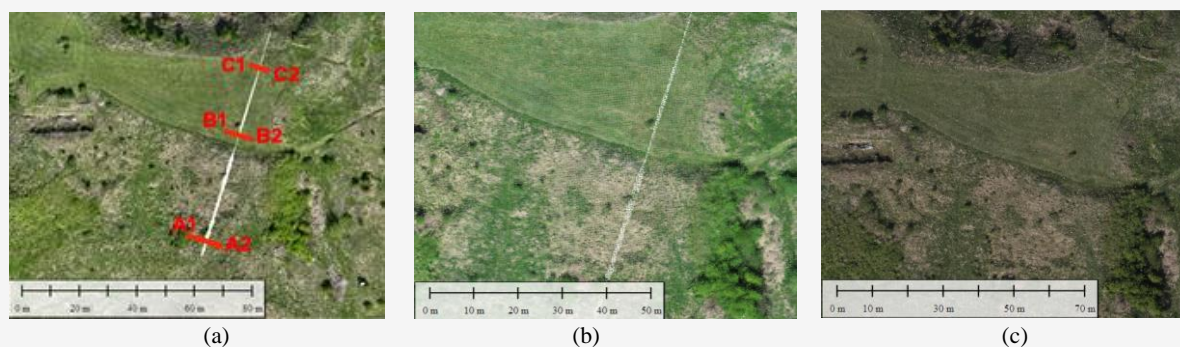
## 5. Results and Discussions

The resulting point clouds obtained from UAV aerial imagery and airborne LiDAR scanning were analyzed. Since the area of the historical and cultural reserve is quite large, during the LiDAR scanning, which was conducted at a low altitude, the UAV was forced to return to the base for battery replacement, after which it resumed scanning from the break point. During aerial imagery at an altitude of 145 meters, the reserve area was captured in a single flight. During the analysis of the point clouds obtained from the two LiDAR systems, a demarcation line between the two scans was identified, indicating where the UAV returned for battery replacement.

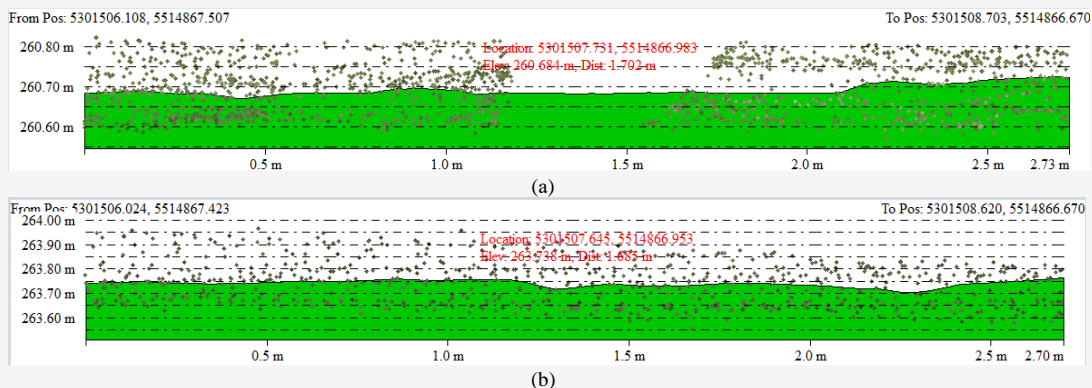
There are no scanning points along this line, suggesting a shift in the UAV's position during the second flight for unknown reasons. It is important to note that the flight plan was designed to cover the entire scanning period, and this line resulted from automatic route resumption. These issues occurred

during scanning with both the DJI Zenmuse L2 and the CHCNAV Alpha Air 450 scanners. In contrast, the point cloud generated from aerial imagery did not exhibit this problem, resulting in a continuous cloud.

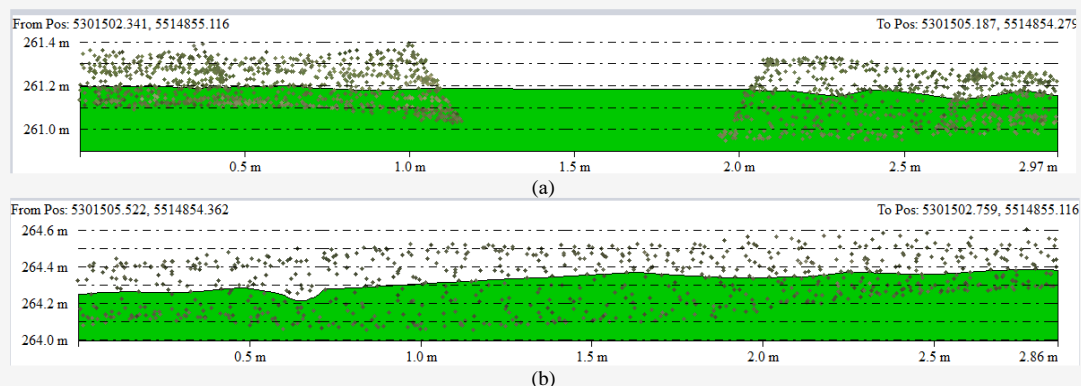
It is known that point clouds built using LiDAR scanning are significantly more accurate than those generated from aerial imagery, leading to more precise Digital Surface Models (DSM). The absence of points in a part of the area poses a significant problem for accurately determining the ground surface in that section, which is especially crucial when studying planar elements of historical and cultural heritage objects. For the analysis of the missing point cloud section compared to the point cloud built from aerial imagery data, profiles A1-A2, B1-B2, and C1-C2 were constructed on each of the generated DSMs (Figure 10). Since the analysis of the point clouds indicated that the absence of points in the scans from the DJI Zenmuse L2 and CHC Alpha Air 450 LiDAR systems was identical, we used the profiles from the DJI Zenmuse L2 LiDAR scanning data and the aerial imagery for further analysis. Figure 11 shows the data for profile A1-A2, Figure 12 for profile B1-B2, and Figure 13 for profile C1-C2. As shown in the constructed profiles, the absence of data in part of the LiDAR scanning profile is clearly interpreted, and it is evident that the elevation values of points generated from aerial imagery differ from those of LiDAR scanning by several meters. Additionally, there is a significant sparseness of points from aerial imagery compared to LiDAR scanning, even though the highest density was programmatically set during the generation of the point cloud from aerial imagery. To accurately construct the DSM using LiDAR scanning data, it was decided to fill the area where the point cloud is missing with points from the aerial imagery.



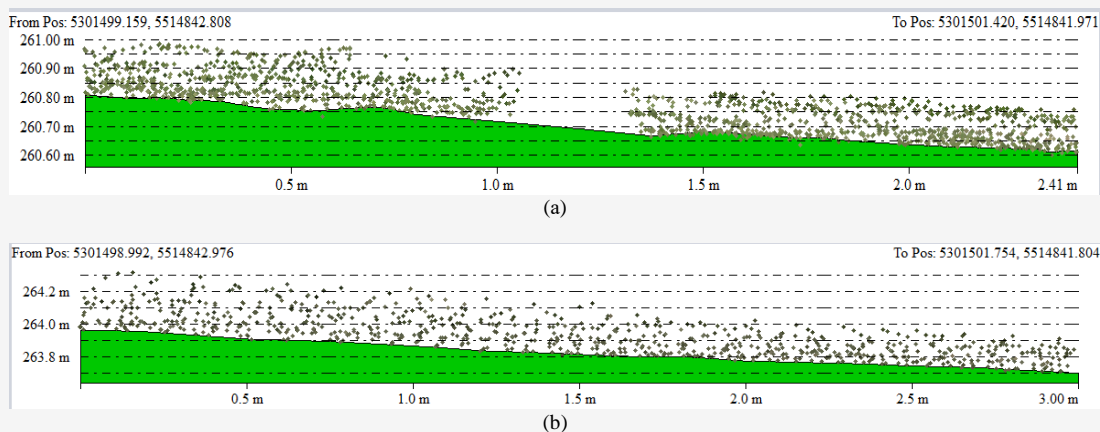
**Figure 10:** Point clouds: (a) LiDAR scanning data using the DJI Zenmuse L2, with profiles for analysis  
 (b) LiDAR scanning data using the CHC Alpha Air 450  
 (c) aerial imagery data



**Figure 11:** Section A1-A2: (a) DSM and point cloud from LiDAR scanning data; (b) DSM and point cloud from aerial imagery data



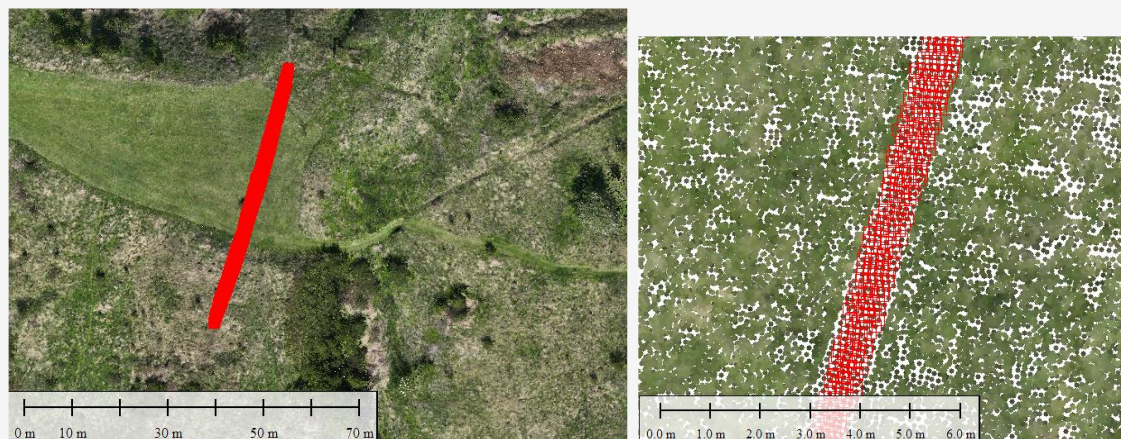
**Figure 12:** Section B1-B2: (a) DSM and point cloud from LiDAR scanning data; (b) DSM and point cloud from aerial imagery data



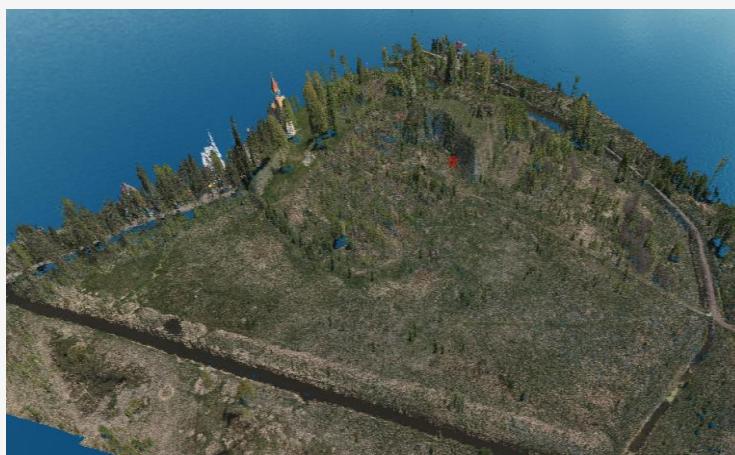
**Figure 13:** Section C1-C2: (a) DSM and point cloud from LiDAR scanning data; (b) DSM and point cloud from aerial imagery data

However, before doing so, it was necessary to align the height of the points from the aerial imagery with the points from the LiDAR scanning. A fragment of the point cloud to be copied was selected, and the heights of all points were programmatically recalculated, assigning the minimum and maximum height values to the nearest laser scanning points (Figure 14). After filling the LiDAR point cloud with

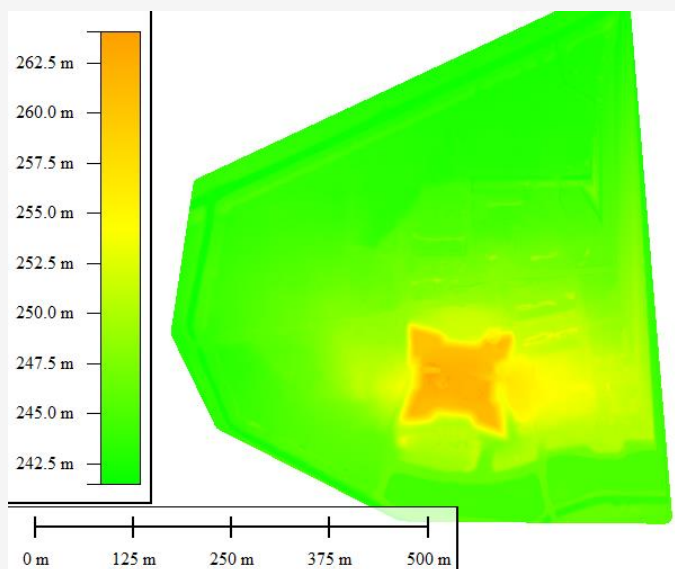
the missing data from the aerial imagery point cloud, an accurate DSM of the Zvenyhorod settlement was constructed (Figure 15). Even though the point density in the problematic area was lower, this approach allowed for the correct representation of all microelements in that area, avoiding the inclusion of erroneous interpolation data in the DSM (Figure 16).



**Figure 14:** Filled areas of the LiDAR point cloud with data from the aerial imagery point cloud (reduced and enlarged fragments)



**Figure 15:** The overall point cloud of the object after correction of the void area



**Figure 16:** Accurate DSM of the Zvenyhorod settlement constructed using LiDAR scanning data combined with aerial imagery

## 6. Conclusion

The synergy of UAV aerial survey methods and LiDAR scanning presents a powerful approach for the study of planar objects of historical and cultural heritage. UAV aerial surveys offer broad coverage and the ability to quickly capture high-resolution imagery over large areas. while LiDAR scanning provides detailed three-dimensional data with high accuracy and precision. Combining these technologies allows researchers to leverage the strengths of both methods. leading to a more comprehensive understanding of the heritage sites under study. This integrated approach enables the creation of accurate digital surface models and orthophotomaps. crucial for detailed analysis and preservation efforts.

One of the primary benefits of this synergy is the enhanced accuracy and completeness of the data. UAV aerial surveys provide a broad and continuous visual record. but may lack the precise elevation information needed for detailed analysis. LiDAR scanning fills this gap by delivering precise topographic data. although it may have limitations in point density and coverage due to operational constraints. By combining these datasets. researchers can address the shortcomings of each method. resulting in a more accurate and detailed representation of the heritage sites. This combined approach is particularly valuable for studying complex sites with varied terrain and intricate features.

The application of UAV aerial surveys and LiDAR scanning together not only improves the accuracy of the data but also facilitates better decision-making for conservation and management. The high-resolution models and maps generated from this combined data can aid in identifying and documenting specific features of historical and cultural significance. Additionally. this method supports the creation of detailed. accurate records of heritage sites. which are essential for monitoring changes over time and informing preservation strategies. Ultimately. the synergy of these technologies provides a robust framework for advancing the study and protection of historical and cultural heritage.

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