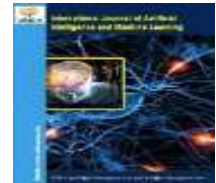




SvedbergOpen
DISSEMINATION OF KNOWLEDGE

International Journal of Artificial Intelligence and Machine Learning

Publisher's Home Page: <https://www.svedbergopen.com/>



Research Paper

Open Access

UAV-Based LiDAR Survey for Accurate 3D Terrain Mapping and Volumetric Analysis

Pushparaj Muthukrishnan¹, Malathi. R^{2*}

¹ Research Scholar, Department of Electronics and Instrumentation Engineering, Annamalai University, Chidambaram, 608 002. E-mail: pushparajasi@gmail.com

² Professor, Department of Electronics and Instrumentation Engineering, Annamalai University, Chidambaram, 608 002. E-mail: aucsd2017@gmail.com

Abstract

Unmanned aerial vehicle (UAV)-based Light Detection and Ranging (LiDAR) has emerged as an effective technology for high-resolution three-dimensional (3D) terrain mapping and volumetric analysis. This study presents an integrated UAV-LiDAR framework that connects aerial data acquisition, sensor calibration, trajectory enhancement, point-cloud preprocessing, ground-surface extraction, digital terrain model (DTM) generation, 3D terrain reconstruction, and volumetric estimation. The proposed approach addresses key factors affecting the reliability of UAV-LiDAR products, including three-dimensional point errors, positioning and trajectory quality, environmental conditions, and surface reconstruction procedures. The reviewed literature demonstrates the application of UAV-LiDAR across forest inventory, DTM generation, complex terrain morphology, urban modelling, and stockpile volume estimation. Quantitative evidence reported in the supplied literature further demonstrates the influence of survey configuration and acquisition geometry on volumetric accuracy. In an experimental stockpile assessment reported by Alsayed et al. (2025), a reference volume of 3.00 m³ was reconstructed with errors ranging from -0.7% to 5.0% across the evaluated UAV-LiDAR configurations, with the lowest reported error of 0.3% obtained using a three-drone configuration at a 1.5 m survey altitude. These findings reinforce the importance of integrating acquisition planning, geometric processing, terrain reconstruction, and quantitative validation rather than evaluating LiDAR performance solely from point-cloud density or visual quality. Overall, UAV-LiDAR provides a flexible and detailed basis for accurate 3D terrain representation and volumetric assessment, provided that sensor configuration, trajectory quality, point-cloud processing, and validation procedures are appropriately controlled.

Keywords: UAV-LiDAR, unmanned aerial vehicle, three-dimensional terrain mapping, point-cloud processing, digital terrain model, 3D reconstruction, volumetric analysis, stockpile volume estimation, LiDAR accuracy, terrain surveying.

1. Introduction

Accurate three-dimensional (3D) terrain representation is essential for surveying, topographic mapping, infrastructure planning, environmental monitoring, earthwork assessment, and volumetric analysis. Conventional field surveying can provide accurate measurements but may require considerable time, personnel, and site access. UAV-based photogrammetry improves data-acquisition efficiency but can be affected by surface texture, illumination, vegetation, and canopy conditions. UAV-based Light Detection and Ranging (LiDAR) provides an effective alternative by acquiring dense three-dimensional point-cloud data with high spatial detail. Early studies demonstrated its potential for complex-environment mapping, while subsequent research examined its accuracy and terrain applications (Wallace et al., 2012; Pilarska et al., 2016).

UAV-LiDAR combines laser scanning with UAV mobility to generate georeferenced point clouds using range, positioning, and trajectory information. These data can support terrain characterization, digital terrain model (DTM) generation, 3D reconstruction, and volume estimation. Increasing drone-LiDAR point density has further expanded its potential for detailed surface mapping (Kellner et al., 2019).

1.1 Background

UAV-mounted laser scanning has broadened the application of airborne LiDAR at relatively small spatial scales. Wallace et al. (2012) demonstrated an early UAV-LiDAR system, while Pilarska et al. (2016) highlighted the potential of lightweight laser scanners for high-resolution surveying. A key advantage of LiDAR is its direct acquisition of three-dimensional range measurements. Although UAV photogrammetry can achieve high accuracy under suitable conditions, its performance may vary with environmental characteristics and canopy openness (Tomaščík et al., 2017). Comparative studies involving photogrammetry, aerial LiDAR, and field surveying have demonstrated the value of UAV technologies for complex terrain reconstruction (Langhammer et al., 2018).

Point-cloud quality remains critical because positioning, trajectory, calibration, and measurement errors can propagate into DTMs and subsequent analyses. Therefore, research has increasingly focused on 3D

point errors, absolute accuracy, calibration, and trajectory enhancement (Mayr et al., 2020; Lassiter et al., 2021; Zhou et al., 2023).

1.2 Need of Research

The growing demand for rapid and accurate 3D surveying requires methods capable of efficiently capturing terrain geometry and supporting quantitative analysis. Conventional surveying can be demanding in large, irregular, inaccessible, or hazardous areas, while image-based UAV mapping may be limited by environmental and surface conditions. UAV-LiDAR provides dense three-dimensional measurements suitable for terrain reconstruction and analysis (Pilarska et al., 2016; Štroner et al., 2023).

This need is particularly important for volumetric applications, where reliable volume estimation depends on accurate surface representation, terrain classification, interpolation, and reference-surface definition. UAV-LiDAR has demonstrated potential for stockpile reconstruction and volume estimation in open and confined environments (Alsayed et al., 2021; Manish et al., 2022; Alsayed & Nabawy, 2022). Therefore, an integrated workflow connecting data acquisition with quantitative 3D measurement is required.

1.3 Motivation

The primary motivation is to improve the efficiency and reliability of high-resolution terrain surveying. UAV-LiDAR combines aerial flexibility with dense laser measurements and supports detailed mapping where conventional surveying may be difficult. Recent research demonstrates its applications in terrain analysis, morphology, urban mapping, and volumetric estimation (Kellner et al., 2019; Bartmiński et al., 2023; Kim & Hong, 2024; El-Diasty et al., 2025).

A further motivation is the need to connect mapping accuracy with practical measurement outcomes. Visually detailed point clouds may still contain errors affecting terrain models. Consequently, calibration, trajectory enhancement, and accuracy assessment are essential for reliable UAV-LiDAR applications (Mayr et al., 2020; Lassiter et al., 2021; Zhou et al., 2023).

1.4 Challenges

UAV-LiDAR surveying involves technical challenges related to sensor calibration, trajectory estimation, georeferencing, point-cloud errors, terrain extraction, and DTM generation. Final model accuracy depends on both system configuration and processing methodology (Mayr et al., 2020; Lassiter et al., 2021).

Environmental conditions can also complicate terrain reconstruction, particularly in vegetated or partially open areas, making comparisons between photogrammetric and LiDAR approaches important (Tomaščík et al., 2017; Štroner et al., 2023). Volumetric analysis introduces additional challenges related to boundary definition, reference-surface reconstruction, and complete representation of the measured object (Alsayed & Nabawy, 2023).

1.5 Influencing Factors

UAV-LiDAR performance is influenced by interconnected factors. **Sensor characteristics** affect measurement capability and point density, while **trajectory and positioning quality** determine spatial consistency. **Calibration parameters** define the geometric relationship between the LiDAR sensor, UAV, and positioning system (Pilarska et al., 2016; Zhou et al., 2023).

Terrain and environmental conditions, point-cloud processing, and ground classification influence the quality of derived terrain models. Furthermore, **surface reconstruction and volume computation procedures** directly affect quantitative outputs such as terrain elevations and stockpile volumes (Bartmiński et al., 2023; Alsayed et al., 2025).

1.6 Conventional Methodologies

Conventional terrain surveying relies primarily on field-based geospatial measurements. While accurate, these methods can become inefficient across extensive, complex, or inaccessible terrain. UAV photogrammetry offers a flexible alternative but depends on image quality and environmental conditions (Tomaščík et al., 2017).

UAV-LiDAR provides a complementary approach through direct three-dimensional range measurements. Research has demonstrated its potential for DTM generation, terrain analysis, urban modelling, and stockpile volume estimation (Štroner et al., 2023; Bartmiński et al., 2023; El-Diasty et al., 2025). However, reliable results require appropriate calibration, trajectory processing, point-cloud analysis, and accuracy assessment. An integrated UAV-LiDAR workflow connecting acquisition, terrain reconstruction, validation, and volumetric analysis therefore provides a suitable foundation for accurate and efficient terrain surveying.

2. Literature Review

The development of UAV-based LiDAR has attracted considerable attention because of its ability to combine flexible aerial data acquisition with high-resolution three-dimensional measurements. Early research established the feasibility of integrating LiDAR sensors with UAV platforms, while subsequent studies evaluated lightweight laser scanners, point-cloud accuracy, terrain reconstruction, calibration, and application-specific performance. The literature demonstrates a progression from system development toward increasingly specialized applications in terrain mapping, digital terrain model (DTM) generation, and volumetric analysis.

Wallace et al. (2012) presented an early UAV-LiDAR system and demonstrated its application to forest inventory. Their work established the feasibility of mounting laser-scanning technology on UAV platforms for acquiring three-dimensional spatial information. Pilarska et al. (2016) subsequently reviewed lightweight laser scanners developed for UAV applications and assessed their potential and accuracy. Their work highlighted the suitability of compact LiDAR systems for airborne surveying while emphasizing the importance of system characteristics in determining achievable accuracy.

The comparison between UAV photogrammetry and LiDAR has also been investigated. Tomašík et al. (2017) evaluated photogrammetric UAV point clouds under partially open forest-canopy conditions, demonstrating that environmental and canopy conditions can influence the quality of photogrammetric reconstruction. Langhammer et al. (2018) examined three-dimensional reconstruction of an abandoned montane reservoir using UAV photogrammetry, aerial LiDAR, and field surveying. Their study demonstrated the value of combining and comparing different 3D surveying techniques for complex terrain reconstruction.

The increasing density of drone-based LiDAR observations has expanded the possibilities for detailed environmental and terrain mapping. Kellner et al. (2019) discussed the opportunities provided by ultra-high-density drone LiDAR for forest remote sensing. This development is particularly relevant to terrain modelling because greater point density can provide more detailed representation of surface characteristics. However, dense point acquisition alone does not guarantee geometric accuracy. Mayr et al. (2020) investigated three-dimensional point errors and change-detection accuracy in UAV laser-scanning data, emphasizing the importance of understanding and controlling point-level errors.

Absolute accuracy has consequently become an important area of UAV-LiDAR research. Lassiter et al. (2021) specifically examined the absolute 3D accuracy of UAS LiDAR surveying. Their work reinforces the importance of evaluating UAV-LiDAR outputs against reliable spatial references rather than relying solely on visual point-cloud quality. This consideration is essential for terrain mapping and volumetric applications, where small elevation errors can propagate into derived surfaces and quantitative measurements.

UAV-LiDAR has also demonstrated practical value for volumetric applications. Alsayed et al. (2021) investigated drone-assisted confined-space inspection and stockpile volume estimation, illustrating the application of UAV-based sensing where conventional access may be difficult. Manish et al. (2022) developed an image-aided LiDAR mapping platform and data-processing strategy for stockpile volume estimation, demonstrating the potential of integrating image and LiDAR information for detailed stockpile mapping. Alsayed and Nabawy (2022) further investigated indoor stockpile reconstruction using drone-borne actuated single-point LiDAR systems, extending UAV-based volume estimation to confined environments.

Calibration and trajectory quality represent another important research direction. Zhou et al. (2023) investigated in-situ calibration and trajectory enhancement for UAV and backpack LiDAR systems used in high-resolution forest inventory. A related study by Zhou et al. (2023) in *Remote Sensing* further examined calibration and trajectory enhancement for fine-resolution forest inventory. Together, these studies demonstrate that reliable 3D mapping depends not only on sensor acquisition but also on the geometric quality of the sensor trajectory and calibration parameters.

Štroner et al. (2023) compared low-cost UAV photogrammetry using the DJI Zenmuse P1 with LiDAR using the DJI Zenmuse L1 for DTM acquisition in forested areas. Their work is particularly relevant to terrain mapping because it directly considers the production of digital terrain information from alternative UAV sensing technologies. Bartmiński et al. (2023) examined the effectiveness of UAV-based LiDAR surveys for developing digital terrain models and conducting topographic texture analyses, further demonstrating the application of LiDAR to detailed terrain characterization.

Volumetric analysis has developed into an important UAV-LiDAR application. Alsayed and Nabawy (2023) reviewed stockpile volume estimation in open and confined environments and identified UAV-based sensing as an important approach for obtaining three-dimensional stockpile information. Their review demonstrates that volume estimation requires consideration of the surveying environment and reconstruction methodology rather than merely the acquisition of point-cloud data. Kim and Hong (2024) examined the usability of UAV LiDAR for analysing karst terrain morphology, showing that UAV-LiDAR can support detailed characterization of complex natural terrain.

Recent research has extended UAV-LiDAR applications toward urban mapping and multi-platform volumetric surveying. El-Diasty et al. (2025) investigated UAV-based LiDAR for urban mapping and modelling applications. Alsayed et al. (2025) experimentally evaluated multi-drone and single-drone systems using one-dimensional LiDAR sensors for stockpile volume estimation, demonstrating continued development of UAV-based volumetric surveying strategies.

Finally, Tuan and Long (2026) discussed advances in topographic mapping with UAVs, including technological developments, challenges, and future prospects. Their work provides a recent perspective on the broader development of UAV technologies for topographic applications. Collectively, the literature indicates that UAV-LiDAR has progressed from experimental platform development toward accurate 3D terrain mapping, DTM generation, morphological analysis, and volumetric estimation. Nevertheless,

accuracy remains dependent on sensor configuration, calibration, trajectory quality, environmental conditions, point-cloud processing, and the methodology used for deriving final terrain or volume measurements.

Table 1: Literature Review of UAV-Based LiDAR for 3D Terrain Mapping and Volumetric Analysis

S. No	Author(s)	Year	Study Focus	Methodology / Application	Major Contribution	Key Limitation / Research Consideration
1	Wallace et al.	2012	UAV-LiDAR system development	Development and application of UAV-LiDAR for forest inventory	Established the feasibility of UAV-mounted LiDAR for 3D data acquisition	Early-generation system; application focused on forest inventory
2	Pilarska et al.	2016	Lightweight UAV laser scanners	Review and accuracy assessment of UAV laser scanners	Examined the potential and accuracy of compact UAV LiDAR systems	Performance depends on scanner characteristics and operating conditions
3	Tomašík et al.	2017	UAV photogrammetric point clouds	Photogrammetric UAV surveying under partially open forest canopy	Demonstrated the influence of canopy conditions on point-cloud quality	Photogrammetric reconstruction can be environmentally dependent
4	Langhammer et al.	2018	3D terrain reconstruction	UAV photogrammetry, aerial LiDAR, and field survey	Demonstrated comparative use of multiple 3D surveying approaches	Complex terrain requires appropriate surveying and reconstruction methods
5	Kellner et al.	2019	Ultra-high-density drone LiDAR	High-density UAV LiDAR for forest remote sensing	Highlighted opportunities enabled by dense drone-LiDAR observations	High point density does not eliminate geometric-error considerations
6	Mayr et al.	2020	3D point errors	Analysis of UAV laser-scanning point errors and change detection	Highlighted the importance of point-level accuracy	Errors can influence derived spatial products
7	Lassiter et al.	2021	Absolute 3D accuracy	Absolute accuracy assessment of UAS LiDAR surveying	Emphasized quantitative evaluation of UAV-LiDAR accuracy	Reliable reference information is required for validation
8	Alsayed et al.	2021	Stockpile volume estimation	Drone-assisted confined-space inspection and volume estimation	Demonstrated UAV application for confined-space stockpile measurement	Confined environments introduce operational challenges
9	Manish et al.	2022	Image-aided LiDAR mapping	Image-aided LiDAR platform and processing strategy	Demonstrated integration of image and LiDAR information	Processing workflow must effectively integrate heterogeneous observations

					for stockpile estimation	
10	Alsayed & Nabawy	2022	Indoor stockpile reconstruction	Drone-borne actuated single-point LiDAR	Extended drone-based volume reconstruction to indoor environments	Indoor surveying presents constraints on system operation
11	Zhou et al.	2023	Calibration and trajectory enhancement	UAV and backpack LiDAR calibration and trajectory refinement	Demonstrated the importance of geometric calibration and trajectory quality	Calibration and trajectory errors remain important sources of uncertainty
12	Zhou et al.	2023	Fine-resolution forest inventory	In-situ calibration and trajectory enhancement	Further developed high-resolution LiDAR acquisition strategies	Application focused on forest inventory
13	Štroner et al.	2023	DTM acquisition	Comparison of UAV photogrammetry and DJI Zenmuse L1 LiDAR	Directly examined UAV technologies for forested-area DTM generation	Terrain and vegetation conditions affect comparative performance
14	Bartmiński et al.	2023	DTM and topographic analysis	UAV-based LiDAR survey	Demonstrated effectiveness for DTM development and topographic texture analysis	Survey effectiveness depends on acquisition and processing quality
15	Alsayed & Nabawy	2023	Stockpile-volume estimation review	Review of open and confined stockpile environments	Consolidated approaches and challenges in UAV-based volume estimation	Different environments require different reconstruction strategies
16	Kim & Hong	2024	Terrain morphology	UAV LiDAR analysis of karst/doline terrain	Demonstrated LiDAR utility for complex terrain morphology	Terrain-specific characteristics influence analysis
17	Alsayed et al.	2025	Multi- and single-drone volume estimation	Experimental evaluation using 1D LiDAR sensors	Compared different drone configurations for stockpile estimation	System configuration affects volumetric surveying performance
18	El-Diasty et al.	2025	Urban mapping and modelling	UAV-based LiDAR	Extended UAV-LiDAR applications to urban 3D mapping	Urban environments introduce additional mapping complexity
19	Tuan & Long	2026	UAV topographic mapping	Review of technologies,	Provides recent	Identifies continuing

				challenges, and prospects	perspective on UAV-based topographic mapping	technological and operational challenges
--	--	--	--	---------------------------	--	--

Literature Synthesis

The reviewed studies reveal three major research directions. First, UAV-LiDAR technology has evolved from system development and lightweight sensor evaluation toward high-density, high-resolution surveying (Wallace et al., 2012; Pilarska et al., 2016; Kellner et al., 2019). Second, accuracy has become a central concern, with research addressing point errors, absolute 3D accuracy, calibration, and trajectory enhancement (Mayr et al., 2020; Lassiter et al., 2021; Zhou et al., 2023). Third, UAV-LiDAR has increasingly been applied to practical 3D measurement problems, including DTM generation, terrain morphology, urban modelling, and stockpile volume estimation (Štroner et al., 2023; Bartmiński et al., 2023; Kim & Hong, 2024; El-Diasty et al., 2025).

However, the literature also indicates that accurate volumetric analysis cannot be considered independently from the quality of 3D terrain reconstruction. Sensor configuration, calibration, trajectory accuracy, environmental conditions, point-cloud processing, and surface-generation procedures collectively influence the reliability of the final measurement. Therefore, the present study focuses on an integrated UAV-LiDAR framework connecting **data acquisition, point-cloud processing, 3D terrain reconstruction, accuracy assessment, and volumetric analysis**.

3. Problem Statement

The increasing demand for accurate and high-resolution three-dimensional terrain information has created a need for efficient surveying technologies capable of representing complex and inaccessible surfaces. Conventional field surveying provides reliable measurements but can be time-consuming and operationally demanding. UAV-based photogrammetry offers an aerial alternative, although point-cloud quality may be affected by image characteristics, vegetation, and environmental conditions (Tomaščík et al., 2017). UAV-LiDAR provides a valuable solution by directly acquiring dense three-dimensional measurements. However, point-cloud density alone does not guarantee accuracy, as point errors, positioning uncertainty, sensor calibration, and trajectory quality can influence geometric consistency (Mayr et al., 2020; Lassiter et al., 2021). Research on calibration and trajectory enhancement further highlights the importance of accurate integration between the LiDAR sensor, positioning system, and UAV trajectory (Zhou et al., 2023). In addition, transforming raw point clouds into representative terrain surfaces and digital terrain models remains a critical challenge, particularly in complex and forested environments (Štroner et al., 2023; Bartmiński et al., 2023).

These challenges become more significant in volumetric analysis, where reliable volume estimation depends on accurate terrain reconstruction and appropriate reference surfaces. UAV-LiDAR has demonstrated strong potential for stockpile measurement and three-dimensional volume estimation in different environments (Alsayed et al., 2021; Manish et al., 2022; Alsayed & Nabawy, 2022; Alsayed et al., 2025). However, existing studies have often examined sensor accuracy, calibration, trajectory enhancement, terrain modelling, and volume estimation separately (Wallace et al., 2012; Pilarska et al., 2016; Mayr et al., 2020; Kim & Hong, 2024). Therefore, this study addresses the need for an integrated UAV-LiDAR methodology that connects accurate 3D data acquisition, point-cloud processing, terrain-surface reconstruction, DTM generation, accuracy assessment, and volumetric computation. The framework is designed around three requirements: accurate and spatially consistent data acquisition, reliable terrain reconstruction, and dependable volumetric analysis. Together, these components establish a systematic approach for high-resolution 3D terrain mapping and reliable volume assessment.

4. Proposed Work

The proposed work develops an integrated UAV-based LiDAR methodology for accurate three-dimensional terrain mapping and volumetric analysis. The framework is designed to connect UAV-LiDAR data acquisition with geometric processing, point-cloud generation, terrain-surface reconstruction, DTM development, accuracy assessment, and volume computation. This integrated structure follows the progression identified in the reviewed literature, where sensor capability, calibration, trajectory quality, point-cloud accuracy, terrain modelling, and volumetric reconstruction are closely related components of reliable UAV-LiDAR surveying (Wallace et al., 2012; Mayr et al., 2020; Lassiter et al., 2021; Zhou et al., 2023).

4.1 Proposed UAV-LiDAR Mapping Framework

The proposed framework consists of six principal stages: **survey planning and UAV-LiDAR data acquisition, calibration and trajectory processing, point-cloud generation and preprocessing, terrain extraction and 3D reconstruction, volumetric analysis, and accuracy assessment**. The stages are sequentially connected because errors introduced during acquisition or geometric processing can propagate into the terrain model and ultimately influence volume estimation.

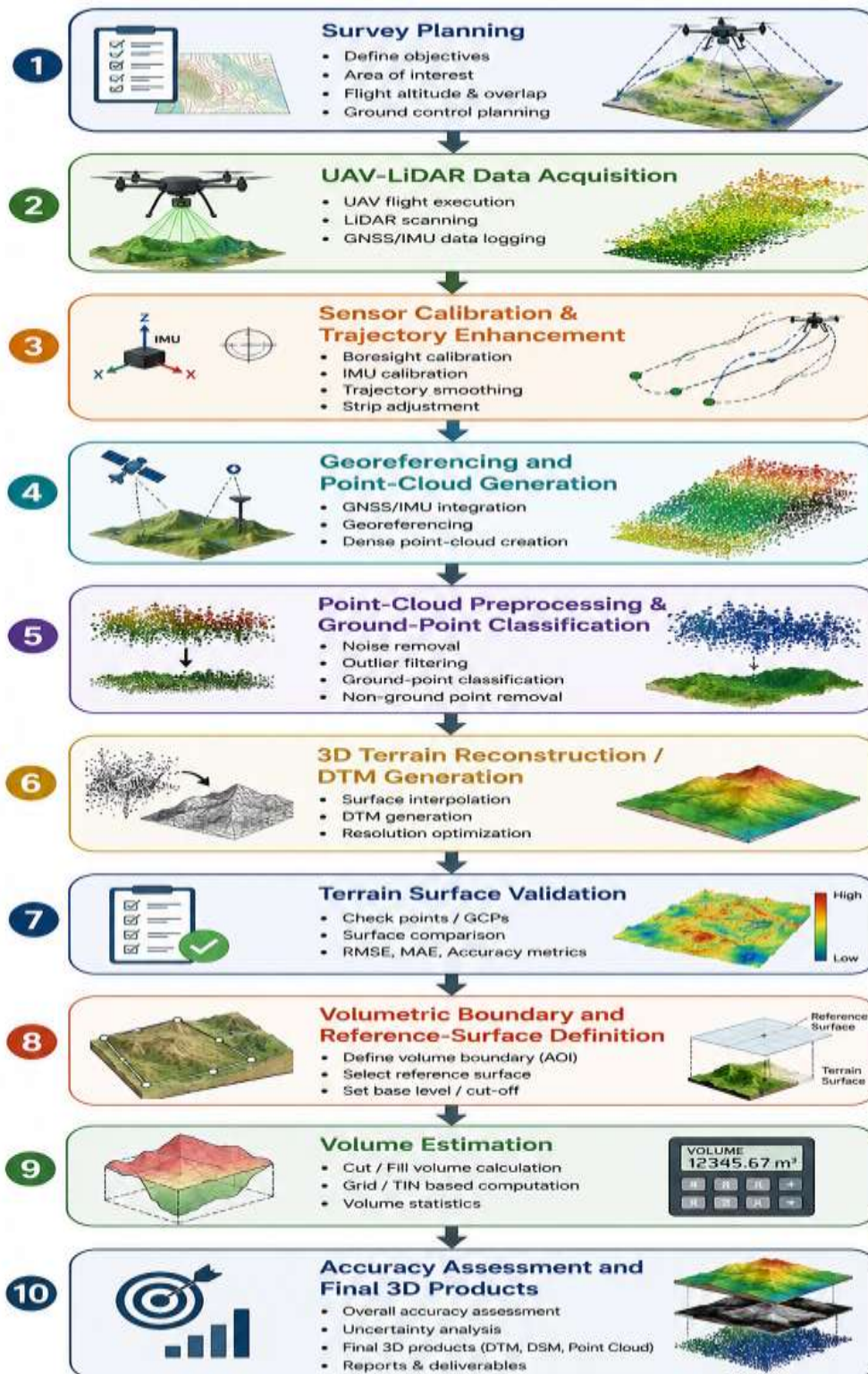


Figure 1: Proposed UAV-LiDAR-Based 3D Terrain Mapping and Volumetric Analysis Framework

The framework is based on the principle that accurate volumetric analysis depends on the quality of the reconstructed three-dimensional surface. Therefore, volume computation is treated as the final stage of a complete spatial-data processing chain rather than as an independent operation.

4.2 UAV-LiDAR Data Acquisition

The first stage involves planning the UAV survey according to terrain characteristics and mapping requirements. The UAV-mounted LiDAR sensor acquires range observations, while positioning and trajectory data provide the spatial reference for locating measurements in three-dimensional space. UAV-LiDAR systems and lightweight laser scanners have demonstrated their suitability for detailed and small-scale airborne surveying (Wallace et al., 2012; Pilarska et al., 2016).

Survey planning should ensure sufficient spatial coverage and observation distribution. For volumetric applications, the complete object surface and relevant boundaries must be captured (Alsayed et al., 2021; Alsayed & Nabawy, 2022).

4.3 Sensor Calibration and Trajectory Enhancement

Following acquisition, sensor calibration and trajectory processing are necessary to ensure geometric consistency. Errors in the LiDAR sensor, positioning system, and UAV trajectory can introduce three-dimensional point errors and affect terrain reconstruction (Mayr et al., 2020; Lassiter et al., 2021).

In-situ calibration and trajectory enhancement are particularly important for high-resolution UAV-LiDAR mapping. Zhou et al. (2023) demonstrated their relevance to fine-resolution LiDAR applications. Therefore, the proposed framework incorporates calibration and trajectory refinement before terrain reconstruction.

4.4 Point-Cloud Generation and Preprocessing

Processed LiDAR observations are transformed into a georeferenced three-dimensional point cloud and subsequently preprocessed for terrain extraction. Since a DTM must represent the ground surface, non-ground objects such as vegetation and structures must be identified and classified.

Increasing drone-LiDAR point density supports detailed spatial characterization, but appropriate geometric processing remains essential (Kellner et al., 2019). Previous studies demonstrate the applicability of UAV-LiDAR point-cloud processing for detailed terrain and DTM characterization (Štroner et al., 2023; Bartmiński et al., 2023).

4.5 3D Terrain Reconstruction and DTM Generation

After preprocessing and classification, ground points are used to reconstruct the three-dimensional terrain surface and generate a continuous digital terrain model. This stage provides the geometric basis for subsequent analysis.

UAV-LiDAR has demonstrated considerable potential for DTM acquisition and terrain analysis, particularly when compared with photogrammetric approaches in complex or forested environments (Štroner et al., 2023; Bartmiński et al., 2023). Detailed terrain reconstruction can also support morphological investigations, as demonstrated in UAV-LiDAR analysis of karst terrain (Kim & Hong, 2024).

4.6 Volumetric Analysis

The reconstructed terrain surface is subsequently used for volume estimation. The calculation requires the surveyed upper surface and a defined reference or base surface. Their elevation difference provides the basis for determining the enclosed volume.

For a discretized terrain surface, volume can conceptually be represented as:

$$V = \sum_{i=1}^n A_i (Z_i - Z_{ri})$$

where V represents the estimated volume, A_i is the area of the i -th surface element, Z_i is the reconstructed surface elevation, and Z_{ri} is the corresponding reference-surface elevation.

The reliability of volume estimation depends on surface quality and boundary definition. UAV-LiDAR and image-aided LiDAR approaches have demonstrated their potential for stockpile mapping and volumetric estimation (Alsayed et al., 2021; Manish et al., 2022). Environmental and reconstruction conditions must also be considered (Alsayed & Nabawy, 2023). Recent multi-drone and single-drone experiments further demonstrate continuing developments in UAV-based volumetric analysis (Alsayed et al., 2025).

4.7 Accuracy Assessment

The final stage evaluates the geometric reliability of the terrain model and derived volume. High point density alone does not guarantee positional accuracy; therefore, quantitative validation is necessary (Mayr et al., 2020; Lassiter et al., 2021).

Where reference measurements are available, LiDAR-derived elevations and terrain surfaces can be compared to quantify discrepancies. Both point-level and surface-level differences should be considered because errors can propagate through interpolation and terrain reconstruction.

4.8 Integrated Research Framework

The proposed methodology establishes a direct relationship between **data acquisition accuracy, geometric processing, terrain reconstruction, and volumetric reliability**. Rather than treating UAV-LiDAR as a single data-collection operation, it integrates the complete workflow from survey planning to quantitative output.

The expected outputs are:

- A georeferenced UAV-LiDAR point cloud.
- A classified ground-point dataset.
- A three-dimensional terrain reconstruction.
- A digital terrain model.
- A volumetric model based on reconstructed and reference surfaces.
- Quantitative accuracy measures.

This integrated approach reflects recent developments emphasizing calibration, trajectory enhancement, accurate terrain modelling, and application-specific 3D analysis (Zhou et al., 2023; Bartmiński et al., 2023;

El-Diasty et al., 2025; Tuan & Long, 2026). It provides a systematic methodological foundation for accurate 3D terrain mapping and reliable volumetric analysis.

5. Results and Discussion

5.1 Experimental Performance of UAV-LiDAR Volume Estimation

The experimental evidence from Alsayed et al. (2025) provides quantitative support for the feasibility of UAV-based LiDAR for three-dimensional stockpile reconstruction. The study evaluated multiple UAV configurations, including two-drone and three-drone formations, a single drone following zigzag trajectories, and a single drone equipped with an actuated 1D LiDAR. A reference trapezoidal-prism stockpile with a volume of 3.00 m^3 was used for the principal experiment.

Table 2 summarizes the reported reconstructed volumes and corresponding errors at two flight altitudes.

Table 2. Reported UAV-LiDAR Volumetric Results for the 3.00 m^3 Reference Stockpile

UAV-LiDAR Method	Volume at 1.5 m (m^3)	Error at 1.5 m (%)	Volume at 2.0 m (m^3)	Error at 2.0 m (%)
Multi-drone (2 drones)	3.03	1.0	3.08	2.7
Multi-drone (3 drones)	3.01	0.3	3.04	1.3
Single drone – zigzag path	3.05	1.7	3.08	2.7
Single drone – finer zigzag path	2.98	-0.7	3.03	1.0
Single drone – actuated 1D LiDAR	3.11	3.7	3.15	5.0
Reference volume	3.00	—	3.00	—

Note. Values are reported experimental results from Alsayed et al. (2025), not measurements from the present proposed study.

The results demonstrate that the **three-drone configuration at 1.5 m altitude produced the smallest reported error of 0.3%**, with an estimated volume of 3.01 m^3 compared with the 3.00 m^3 reference. The corresponding absolute volume difference was only 0.01 m^3 . The two-drone configuration produced a 1.0% error at the same altitude. At 2.0 m, the three-drone configuration retained relatively high accuracy, with a reported error of 1.3%.

The single-drone configurations also produced relatively small errors when the LiDAR followed suitable scanning trajectories. The finer zigzag trajectory produced an error of -0.7% at 1.5 m and 1.0% at 2.0 m. The negative value indicates that the reconstructed volume was slightly lower than the reference volume rather than indicating that the method failed to reconstruct the stockpile. In contrast, the actuated 1D-LiDAR configuration produced larger errors of 3.7% and 5.0% at 1.5 and 2.0 m, respectively.

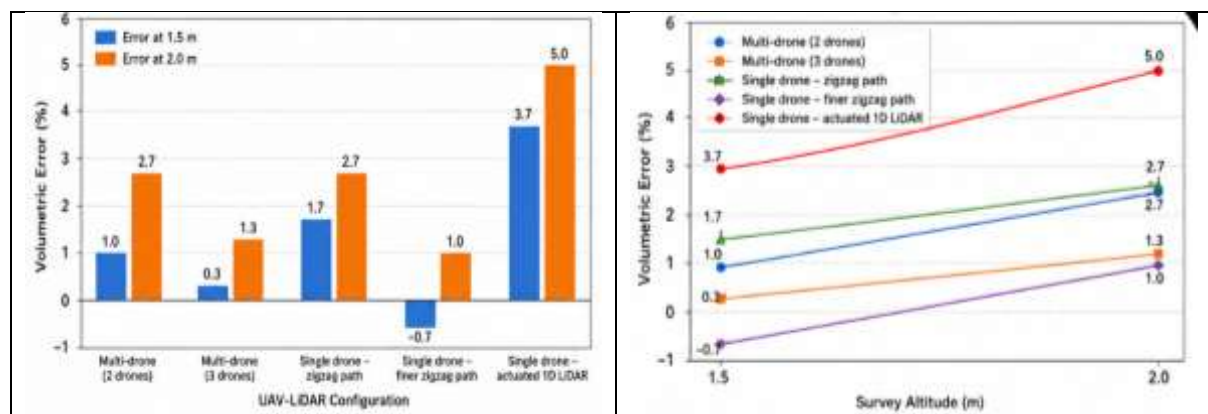


Figure 2. Volumetric Error at Different UAV Configurations

Figure 2 highlights the differences among the tested configurations. The three-drone approach achieved the lowest positive error, whereas the actuated 1D-LiDAR approach produced the largest error at the 1.5 m altitude. The results indicate that scanning configuration and trajectory design can substantially influence the quality of the reconstructed surface.

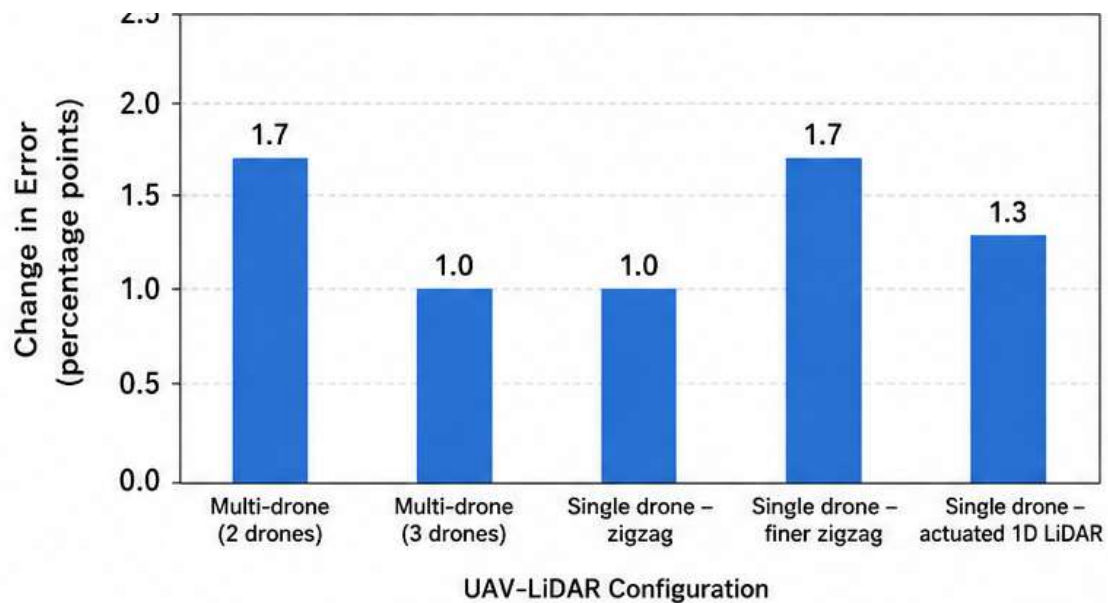
5.2 Effect of Survey Altitude

The comparison between 1.5 m and 2.0 m provides an additional indication of the influence of UAV operating altitude on volumetric reconstruction. For the two-drone configuration, the error increased from **1.0% to 2.7%**, representing a 1.7 percentage-point increase. For the three-drone configuration, the error increased from **0.3% to 1.3%**. The single-drone zigzag configuration similarly increased from **1.7% to 2.7%**.

The finer zigzag configuration showed a smaller change, from -0.7% at 1.5 m to 1.0% at 2.0 m. The actuated LiDAR configuration showed the greatest deterioration, with error increasing from **3.7% to 5.0%**. These results suggest that increasing the survey altitude does not necessarily preserve the same reconstruction accuracy, particularly for configurations where point distribution and sensor geometry become less favorable.

Table 3. Change in Reported Volumetric Error Between 1.5 m and 2.0 m

Method	Error at 1.5 m (%)	Error at 2.0 m (%)	Change (percentage points)
Multi-drone (2 drones)	1.0	2.7	+1.7
Multi-drone (3 drones)	0.3	1.3	+1.0
Single drone – zigzag	1.7	2.7	+1.0
Single drone – finer zigzag	-0.7	1.0	+1.7
Single drone – actuated 1D LiDAR	3.7	5.0	+1.3



The overall pattern indicates that the lower survey altitude generally produced smaller volumetric errors in this particular experimental setup. However, these values should not be generalized to all UAV-LiDAR surveys because altitude-performance relationships depend on sensor characteristics, field of view, trajectory, surface geometry, point density, and processing methodology.

5.3 Effect of UAV Configuration on Survey Efficiency

Accuracy must be considered together with operational efficiency. The reported trajectory distances in the experiment were **8 m** for the longest multi-drone trajectory, approximately **14 m** for the standard single-drone zigzag trajectory, **20 m** for the finer zigzag trajectory, and **10 m** for the actuated 1D-LiDAR approach. At the specified maximum velocity of 0.1 m/s, these corresponded to approximately **80 s, 140 s, 200 s, and 100 s**, respectively.

Table 4. Reported Trajectory and Approximate Mission Duration

UAV-LiDAR configuration	Approx. trajectory distance (m)	Approx. mission duration (s)
Multi-drone	8	80
Single drone – zigzag	14	140
Single drone – finer zigzag	20	200
Single drone – actuated 1D LiDAR	10	100

The results demonstrate an important trade-off between **coverage, accuracy, and operational time**. The multi-drone configuration required the shortest reported trajectory and therefore approximately 80 s for the longest individual drone path. The standard and finer single-drone zigzag approaches required approximately 140 s and 200 s, respectively. The actuated configuration reduced the trajectory to approximately 100 s but exhibited larger volumetric errors.

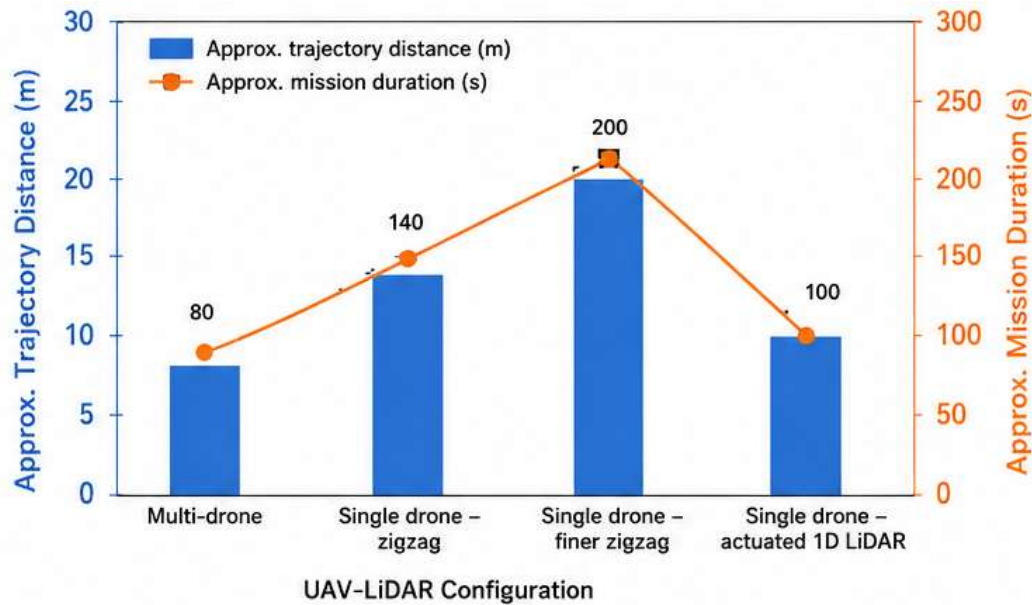


Figure 3. Approximate Mission Duration by UAV Configuration

The efficiency comparison shows that a longer trajectory can improve spatial coverage but increases mission duration. This is particularly important for UAV operations because battery limitations constrain the achievable survey distance. In the reported experiment, the Crazyflie 2.1 platform had a maximum flight duration of approximately **7 minutes**, while at 1 m/s it could cover more than 400 m under the stated conditions.

5.4 Accuracy of 3D Reconstruction

The numerical results indicate that volumetric accuracy is strongly associated with the quality of the reconstructed 3D surface. The three-drone configuration achieved an error of only 0.3% at 1.5 m, corresponding to a reconstructed volume of 3.01 m³. This represents a difference of approximately 0.01 m³ from the reference volume.

The results also demonstrate that increasing the number of drones is not the only factor affecting accuracy. The finer single-drone zigzag configuration produced a -0.7% error at 1.5 m, which was lower in absolute magnitude than the 1.0% error obtained using two drones. Therefore, **trajectory geometry and point distribution can be as important as the number of sensing platforms**.

The actuated 1D-LiDAR configuration illustrates another important limitation. Although its trajectory was shorter than the single-drone zigzag approaches, its volumetric errors were substantially larger. Alsayed et al. (2025) attributed this deterioration primarily to outlier points and LiDAR bias associated with non-vertical scanning angles.

5.5 Path Accuracy and Point-Cloud Reliability

The experimental study also reported an average deviation of **0.23% between desired and actual drone paths** within the multi-drone formation. This provides quantitative evidence that trajectory control can be achieved with relatively small positional deviation under the tested experimental conditions.

This finding is relevant to the proposed UAV-LiDAR framework because trajectory quality directly affects the spatial registration of LiDAR observations. The literature reviewed earlier similarly identifies point errors, absolute 3D accuracy, calibration, and trajectory enhancement as important elements of reliable UAV-LiDAR mapping (Mayr et al., 2020; Lassiter et al., 2021; Zhou et al., 2023).

Table 5. Key Quantitative Indicators Reported in the Experimental Study

Indicator	Reported value
Reference stockpile volume	3.00 m ³
Lowest reported volumetric error	0.3%
Three-drone volume at 1.5 m	3.01 m ³
Three-drone error at 2.0 m	1.3%
Highest error in principal comparison	5.0%
Average error reported for multi-/single-drone zigzag approaches	1.3%
Average error reported for actuated 1D-LiDAR approach	4.4%
Average desired-vs.-actual path deviation	0.23%
Longest multi-drone trajectory	8 m
Finer single-drone trajectory	20 m

Approximate multi-drone mission duration	80 s
Approximate finer-zigzag mission duration	200 s
Approximate maximum flight duration of tested micro-UAV	7 min

The reported average volumetric error of **1.3%** for the multi-drone and closely related single-drone zigzag approaches compares favorably with the **4.4%** average error reported for the actuated 1D-LiDAR approach. The latter's higher error was associated with surface-reconstruction outliers and LiDAR bias when scanning at non-vertical angles.

5.6 Discussion

The numerical evidence supports the central premise that UAV-LiDAR can provide accurate three-dimensional reconstruction when acquisition geometry, trajectory, and point-cloud processing are properly controlled, while also demonstrating that sensor deployment alone does not determine mapping accuracy. In the 3.00 m³ reference experiment, volumetric errors ranged from **-0.7% to 5.0%**, with the three-drone configuration achieving the lowest error of **0.3%** at 1.5 m; the actuated 1D-LiDAR results further showed that shorter scanning paths do not necessarily ensure better accuracy. These findings are consistent with studies emphasizing geometric errors, absolute 3D validation, calibration, trajectory quality, and reconstructed-surface accuracy in UAV-LiDAR applications (Mayr et al., 2020; Lassiter et al., 2021; Zhou et al., 2023; Manish et al., 2022; Alsayed & Nabawy, 2023). Therefore, **survey planning → trajectory control → LiDAR acquisition → point-cloud processing → surface reconstruction → volume computation** should be treated as an integrated workflow, as errors at any stage can affect the final volumetric result. However, because the experiments involved a small 3.00 m³ trapezoidal prism in a controlled indoor environment, the reported accuracy values should not be directly generalized to outdoor terrain or large landscapes. Instead, they provide quantitative evidence for evaluating UAV-LiDAR configurations and reinforce the need for accuracy assessment beyond the visual quality of point clouds and 3D models.

6. Conclusion

UAV-based LiDAR provides an effective framework for high-resolution three-dimensional terrain mapping and volumetric analysis by integrating flexible aerial surveying with dense spatial measurements. The reviewed literature demonstrates its applicability to DTM generation, complex terrain characterization, urban modelling, and stockpile volume estimation, while also highlighting the importance of sensor calibration, trajectory enhancement, point-cloud processing, and quantitative accuracy assessment (Wallace et al., 2012; Lassiter et al., 2021; Zhou et al., 2023; Bartmiński et al., 2023). The quantitative results discussed from Alsayed et al. (2025) further demonstrate that survey configuration and acquisition geometry can substantially influence volumetric accuracy, with errors ranging from -0.7% to 5.0% for the evaluated configurations. Overall, the findings support an integrated UAV-LiDAR workflow in which accurate data acquisition, geometric correction, terrain reconstruction, DTM generation, and surface-based volume computation are treated as interconnected stages. Such an approach can improve the reliability and efficiency of 3D terrain surveying and provide a practical foundation for accurate volumetric assessment across suitable open and confined surveying environments.

7. Future Scope

The future development of UAV-based LiDAR for terrain mapping and volumetric analysis can focus on improving geometric accuracy, automation, and operational efficiency. Further research can investigate optimized UAV flight trajectories, improved sensor calibration, and trajectory-enhancement techniques to reduce three-dimensional positioning errors and improve the consistency of derived terrain surfaces (Mayr et al., 2020; Lassiter et al., 2021; Zhou et al., 2023). Integration of LiDAR with complementary imaging systems can also be explored for improving point-cloud interpretation and volumetric reconstruction, as demonstrated by image-aided LiDAR approaches for stockpile estimation (Manish et al., 2022). Future studies may additionally extend UAV-LiDAR applications from controlled stockpile environments to larger and more complex natural, forested, urban, and morphologically variable terrains, building on existing research in DTM generation, terrain morphology, and urban modelling (Štroner et al., 2023; Kim & Hong, 2024; El-Diasty et al., 2025). The development of multi-UAV configurations and lightweight sensing systems may further improve survey coverage and reduce acquisition time, while recent work on UAV-based topographic mapping indicates continued opportunities for technological advancement (Alsayed et al., 2025; Tuan & Long, 2026). Future research should ultimately emphasize standardized accuracy assessment and validation procedures so that improvements in point-cloud quality can be directly related to the reliability of derived terrain models and volumetric measurements.

References:

1. L. Wallace, A. Lucieer, C. Watson, and D. Turner, "Development of a UAV-LiDAR system with application to forest inventory," *Remote Sensing*, vol. 4, no. 6, pp. 1519–1543, 2012. [Online]. Available: <https://doi.org/10.3390/rs4061519>

2. M. Pilarska, W. Ostrowski, K. Bakula, K. Górski, and Z. Kurczyński, "The potential of light laser scanners developed for unmanned aerial vehicles – The review and accuracy," *Int. Arch. Photogramm., Remote Sens. Spatial Inf. Sci.*, vol. XLII-2/W2, pp. 87–95, 2016. [Online]. Available: <https://doi.org/10.5194/isprs-archives-XLII-2-W2-87-2016>
3. J. Tomaščík, M. Mokroš, Š. Saloň, F. Chudý, and D. Tunák, "Accuracy of photogrammetric UAV-based point clouds under conditions of partially-open forest canopy," *Forests*, vol. 8, no. 5, Art. no. 151, 2017. [Online]. Available: <https://doi.org/10.3390/f8050151>
4. J. Langhammer, B. Janský, J. Kocum, and R. Minařík, "3-D reconstruction of an abandoned montane reservoir using UAV photogrammetry, aerial LiDAR and field survey," *Applied Geography*, vol. 98, pp. 9–21, 2018.
5. J. R. Kellner, J. Armston, M. Birrer, *et al.*, "New opportunities for forest remote sensing through ultra-high-density drone LiDAR," *Surveys in Geophysics*, vol. 40, pp. 959–977, 2019. [Online]. Available: <https://doi.org/10.1007/s10712-019-09529-9>
6. Mayr, M. Bremer, and M. Rutzinger, "3D point errors and change detection accuracy of unmanned aerial vehicle laser scanning data," *ISPRS Ann. Photogramm., Remote Sens. Spatial Inf. Sci.*, vol. V-2-2020, pp. 765–772, 2020. [Online]. Available: <https://doi.org/10.5194/isprs-annals-V-2-2020-765-2020>
7. H. A. Lassiter, B. Wilkinson, A. Gonzalez Perez, and C. Kelly, "Absolute 3D accuracy assessment of UAS LiDAR surveying," *Int. Arch. Photogramm., Remote Sens. Spatial Inf. Sci.*, vol. XLIV-M-3-2021, pp. 105–111, 2021. [Online]. Available: <https://doi.org/10.5194/isprs-archives-XLIV-M-3-2021-105-2021>
8. Alsayed, A. Yunusa-Kaltungo, M. K. Quinn, F. Arvin, and M. R. A. Nabawy, "Drone-assisted confined space inspection and stockpile volume estimation," *Remote Sensing*, vol. 13, no. 17, Art. no. 3356, 2021. [Online]. Available: <https://doi.org/10.3390/rs13173356>
9. R. Manish, S. M. Hasheminasab, J. Liu, Y. Koshan, J. A. Mahlberg, Y.-C. Lin, R. Ravi, T. Zhou, J. McGuffey, T. Wells, D. Bullock, and A. Habib, "Image-aided LiDAR mapping platform and data processing strategy for stockpile volume estimation," *Remote Sensing*, vol. 14, no. 1, Art. no. 231, 2022. [Online]. Available: <https://doi.org/10.3390/rs14010231>
10. Alsayed and M. R. A. Nabawy, "Indoor stockpile reconstruction using drone-borne actuated single-point LiDARs," *Drones*, vol. 6, no. 12, Art. no. 386, 2022. [Online]. Available: <https://doi.org/10.3390/drones6120386>
11. T. Zhou, R. Manish, S. Fei, and A. Habib, "In-situ calibration and trajectory enhancement of UAV and backpack LiDAR systems for high-resolution forest inventory," *Int. Arch. Photogramm., Remote Sens. Spatial Inf. Sci.*, vol. XLVIII-1/W1-2023, pp. 595–602, 2023. [Online]. Available: <https://doi.org/10.5194/isprs-archives-XLVIII-1-W1-2023-595-2023>
12. T. Zhou, R. Ravi, Y.-C. Lin, R. Manish, S. Fei, and A. Habib, "In situ calibration and trajectory enhancement of UAV and backpack LiDAR systems for fine-resolution forest inventory," *Remote Sensing*, vol. 15, no. 11, Art. no. 2799, 2023. [Online]. Available: <https://doi.org/10.3390/rs15112799>
13. M. Štroner, R. Urban, T. Křemen, and J. Braun, "UAV DTM acquisition in a forested area – Comparison of low-cost photogrammetry (DJI Zenmuse P1) and LiDAR solutions (DJI Zenmuse L1)," *European Journal of Remote Sensing*, vol. 56, no. 1, 2023. [Online]. Available: <https://doi.org/10.1080/22797254.2023.2179942>
14. Alsayed and M. R. A. Nabawy, "Stockpile volume estimation in open and confined environments: A review," *Drones*, vol. 7, no. 8, Art. no. 537, 2023. [Online]. Available: <https://doi.org/10.3390/drones7080537>
15. P. Bartmiński, M. Siłuch, and W. Kociuba, "The effectiveness of a UAV-based LIDAR survey to develop digital terrain models and topographic texture analyses," *Sensors*, vol. 23, no. 14, Art. no. 6415, 2023.
16. J. Kim and I. Hong, "Evaluation of the usability of UAV LiDAR for analysis of karst (doline) terrain morphology," *Sensors*, vol. 24, no. 21, Art. no. 7062, 2024.
17. Alsayed, F. Bana, F. Arvin, M. K. Quinn, and M. R. A. Nabawy, "Experimental evaluation of multi- and single-drone systems with 1D LiDAR sensors for stockpile volume estimation," *Aerospace*, vol. 12, no. 3, Art. no. 189, 2025. [Online]. Available: <https://doi.org/10.3390/aerospace12030189>
18. M. El-Diasty, A. Al-Hashim, and R. Abdalla, "UAV-based LiDAR system for urban mapping and modelling applications," *Int. Arch. Photogramm., Remote Sens. Spatial Inf. Sci.*, vol. 48, pp. 13–17, 2025.
19. Tuan and Q. Long, "Advancing topographic mapping with UAVs: Technologies, challenges, and prospects," *International Journal of Geoinformatics*, vol. 22, no. 4, pp. 44–63, 2026. [Online]. Available: <https://doi.org/10.52939/ijg.v22i4.4938>