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A Review of UAV Photogrammetry Applications in Mining: Structural Mapping and Surface Monitoring

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Abstract

Open-pit mining presents significant challenges due to steep topography, structural discontinuities, and rapidly changing surface conditions. UAV-based photogrammetry has emerged as an effective, cost-efficient solution for acquiring high-resolution spatial data in such complex environments. While numerous studies have explored specific applications of UAV photogrammetry in mining, a comprehensive synthesis addressing the full spectrum of technologies and operational strategies remains lacking. This review fills that gap by presenting an analysis of 33 representative studies published between 2017 and 2025, focusing on the integration of UAV photogrammetry, Structure-from-Motion (SfM), deep learning, and airborne LiDAR for monitoring and modeling open-pit mines. Key innovations include the use of oblique imagery, which provides superior vertical and occluded feature capture critical to mining operations. Quantitative comparison highlights that hybrid SfM–AI workflows achieve horizontal and vertical accuracies of ±2.9 cm and ±6.4 cm, respectively, with volumetric error rates below 5%. The application domains discussed include slope stability assessment, step-line and discontinuity extraction, volumetric monitoring, bench reconstruction, and reclamation analysis. Additionally, the paper examines the challenges of data noise, occlusion, and multi-temporal alignment, while proposing solutions to these issues. Finally, the review outlines future research directions, including real-time processing, AI-driven feature recognition, and geodynamic simulation, confirming that UAV photogrammetry is evolving into a cornerstone technology for intelligent, automated, and high-precision monitoring in sustainable open-pit mining.

1. Introduction

Open-pit mines, as major sources of mineral extraction, face persistent challenges related to slope stability, topographic change detection, and the accurate management of extracted and waste materials. The vast, irregular, and often hazardous conditions of these environments underscore the need for precise, safe, and efficient spatial monitoring and modeling techniques.

Photogrammetry has long served as a cornerstone in engineering surveying for generating three-dimensional spatial information. However, conventional ground-based or aerial approaches remain limited by terrain inaccessibility, high operational costs, and weather dependency, reducing their effectiveness in complex and dynamic mining settings.

In recent years, the integration of unmanned aerial vehicles (UAVs) into remote sensing workflows has revolutionized spatial data acquisition and processing. UAVs provide flexible flight planning, rapid image capture, and safe operation in steep or unstable areas, enabling the generation of dense, high-accuracy 3D point clouds. When combined with technologies such as Structure-from-Motion (SfM), LiDAR, and deep learning, UAV photogrammetry enhances automation and analytical capacity, supporting both spatial reconstruction and geotechnical interpretation.

The application of oblique imaging strategies has further advanced geometric precision in areas with sharp slopes, vertical faces, and complex pit geometries. Multi-angle datasets enable detailed modeling of benches, steps, and slope walls—key features for geomechanical evaluation and mine design optimization.

Despite its growing adoption, UAV photogrammetry in open-pit mining still faces methodological and operational challenges. Integration of multi-source data (e.g., SfM, LiDAR, and AI-based analytics) remains fragmented, and comprehensive assessments of accuracy, cost-efficiency, and field adaptability are limited. Moreover, most prior studies focus on isolated applications—such as mapping or volume estimation—rather than developing a unified, workflow-based framework linking data acquisition, processing, and decision support.

This paper addresses these gaps by presenting a comprehensive and quantitative review of UAV photogrammetry applications in open-pit mining. It consolidates advancements in imaging technologies, algorithmic developments, and intelligent analysis, with emphasis on oblique photogrammetry, multi-source data fusion, and AI-assisted feature extraction. Unlike previous reviews that primarily provided descriptive overviews, this study offers a critical synthesis of technological trends and proposes a research roadmap toward intelligent, automated, and real-time monitoring systems for sustainable mining operations.

2. Review of Photogrammetric Technologies

The technological foundation of UAV-based photogrammetry integrates advanced imaging systems, sensor platforms, and computational algorithms to achieve precise 3D modeling and surface monitoring in mining environments. Accurate observation of open-pit mines demands the combination of efficient data acquisition, multi-source integration, and automated analytical frameworks. This section presents a comprehensive review of the key technologies underpinning modern UAV photogrammetry—namely UAV platforms, Structure-from-Motion (SfM), airborne LiDAR, oblique imagery, deep learning, and specialized processing software. Each technology plays a distinct yet complementary role in improving geometric accuracy, spatial completeness, and automation of geospatial analysis within mining applications.

2.1 Unmanned Aerial Vehicles (UAVs)

UAVs have revolutionized remote sensing and surveying by enabling high-resolution, low-cost, and flexible data collection in complex and hazardous terrains. Systems such as the DJI

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Phantom 4 RTK and Matrice 300 RTK—equipped with GNSS/RTK positioning modules—can achieve centimeter-level georeferencing accuracy and stability in repeated surveys (Tong et al., 2015; Cao et al., 2023). Multi-rotor UAVs are favored for high-precision local surveys, while fixed-wing platforms remain suitable for large-scale mapping. Recent work by Zhang et al. (2017) and Sayab et al. (2018) demonstrated that UAV photogrammetry can achieve sub-decimeter accuracy in steep, fractured, and previously inaccessible zones. However, the accuracy of UAV mapping still depends on flight altitude, overlap ratios, and environmental lighting, requiring adaptive mission planning in mining contexts (Wierzbicki, 2018).

2.2 Structure from Motion (SfM)

Structure-from-Motion has become the computational core of modern photogrammetry, capable of producing dense point clouds through feature matching across overlapping imagery. SfM minimizes the need for ground control points (GCPs) and laser scanning, providing a flexible and cost-efficient alternative for high-resolution topographic modeling. Studies such as Sayab et al. (2018), Mao et al. (2022), and Le Roux et al. (2025) confirmed that SfM-based reconstructions can achieve mean RMSE values under 0.06 m in complex pit geometries. Nevertheless, errors can increase in low-texture or shadowed regions, prompting hybrid workflows that fuse SfM with AI-based filtering and LiDAR-derived control points (Cao et al., 2023; Zhong and Liu, 2025).

2.3 Airborne LiDAR

LiDAR (Light Detection and Ranging) complements UAV photogrammetry by providing direct range measurements that enhance vertical accuracy and terrain fidelity. When integrated with UAV imagery, LiDAR delivers more reliable digital terrain models (DTMs) and volumetric estimates in areas with dense vegetation or steep slopes. Mao et al. (2022) and Jafari and Dorafshan (2025) reported that UAV–LiDAR fusion improved vertical RMSE by up to 35–40% compared to SfM-only workflows (Qing et al., 2025; Jafari and Dorafshan, 2025). However, LiDAR systems are cost-intensive and require higher payload capacity, which limits their deployment in routine mine monitoring missions.

2.4 Oblique Imagery

Oblique photogrammetry has become one of the most transformative developments in UAV-based 3D modeling, especially for open-pit mining where vertical and overhanging surfaces dominate the terrain. Unlike traditional nadir imaging that primarily captures horizontal features, oblique imagery employs cameras tilted between 30° and 60° from nadir, providing lateral perspectives that expose pit walls, benches, and structural discontinuities otherwise hidden from top-down views. This multi-angle visibility enables the reconstruction of complete and geometrically accurate 3D models even in areas with complex morphology, steep slopes, or occlusions caused by mining infrastructure (Wierzbicki, 2018; Wang et al., 2020; Caihuan and Wendong, 2020; Lu et al., 2021).

Multi-camera oblique UAV systems, typically configured with one vertical and four oblique sensors, have become standard for comprehensive mine coverage. Such systems can capture imagery with up to 80% forward and 70% side overlap, allowing 360° spatial coverage and minimizing blind zones in rugged pit geometries (Wierzbicki, 2018; Wang et al., 2020). Wang et al. (2020) and Mao et al. (2022) demonstrated that oblique UAV imaging improves edge continuity and slope delineation compared to nadir-only datasets. Moreover, geometric accuracy evaluations by Lu et al. (2021) and Cui et al. (2024) reported mean horizontal and vertical accuracies of ±2.9 cm and ±6.4 cm, respectively—sufficient for direct integration into mine design and safety analysis software (Vulcan, Surpac, and MineScape) (Wang et al., 2020; Lu et al., 2021).

Beyond geometric reconstruction, oblique imagery supports multi-temporal analysis, enabling volumetric change detection, backfill tracking, and excavation monitoring across different mining stages. Algorithms using digital surface model (DSM) differencing, noise filtering, and regional connectivity have been developed to isolate true morphological changes from artifacts (Cao et al., 2023). For construction and reclamation projects, periodic oblique imaging facilitates DLG- and mesh-based comparisons, enabling accurate quantification of cut-and-fill operations, structure demolition, and earthwork progress (Liu and Tan, 2024; Zhong and Liu, 2025).

In the context of geohazard and slope stability monitoring, temporal oblique datasets offer dynamic insights into slope deformation processes. Liu et al. (2024a) applied GDEM-GAVA simulations driven by oblique UAV data to analyze landslide evolution, identifying dual accumulation zones—upper-step and middle-step regions—with sliding volumes exceeding 30,000 m^3. Such results illustrate the unique capacity of oblique imagery to provide both visual and numerical input for geotechnical risk assessment (Liu et al., 2024a).

Ecological reclamation monitoring has also benefited substantially from oblique photogrammetry. Zhong and Liu (2025) demonstrated that UAV oblique datasets captured over multiple time phases (2022–2024) enable digital visualization of reclamation progress with ground sampling distance (GSD) of 2.5 cm/pixel and volumetric accuracy within 5%. These results show the effectiveness of oblique imagery for digital supervision, earthwork validation, and compliance assessment with reclamation design plans (Caihuan and Wendong, 2020; Deng, 2021; Zhong and Liu, 2025).

Despite its strong potential, oblique photogrammetry faces practical limitations related to increased data volume, higher computational demands, and the need for advanced image alignment algorithms to mitigate perspective distortion. However, ongoing research integrating oblique imagery with deep learning, LiDAR fusion, and real-time 3D reconstruction workflows continues to expand its applicability for intelligent mining. Overall, oblique UAV photogrammetry provides structurally rich datasets, enhances the geometric completeness of mine models, and serves as a cornerstone technology for the next generation of intelligent, automated open-pit monitoring systems.

2.5 Deep Learning

Deep learning has emerged as a transformative component of photogrammetric workflows, facilitating automation in feature detection, classification, and change analysis. CNN-based architectures such as U-Net, PointNet++, and 1D-CNN have achieved classification accuracies exceeding 90% in fracture detection, slope instability recognition, and reclamation monitoring (Yadav, 2020; Jafari and Dorafshan, 2025; Cao et al., 2023). Integration of deep learning with SfM pipelines enables predictive modeling and segmentation of slope deformations using historical UAV datasets (Tangadzani et al., 2024; Le Roux et al., 2025). Furthermore, AI-assisted photogrammetry enhances efficiency in identifying geomorphic patterns and reducing manual interpretation errors across large datasets.

2.6 Specialized Software

Photogrammetric and analytical software form the operational backbone of UAV data processing. Commercial tools such as Pix4D, Agisoft Metashape, and DJI Terra dominate practical workflows for DSM/DEM generation, mesh reconstruction, and volumetric analysis. Open-source alternatives including Cloud Compare, OpenDroneMap, and Micmac are increasingly employed for algorithm customization and reproducibility. Analytical environments like MATLAB and Python (via TensorFlow, PyTorch, and Open3D) enable integration of deep learning, statistical modeling, and large-scale point cloud analytics, allowing fully automated pipelines for mining applications (Cui et al., 2024; Jafari and Dorafshan, 2025; Cao et al., 2023; Caihuan and Wendong, 2020).

To provide an integrated overview of the reviewed literature and link the discussed technologies into a unified framework, Figure 1 illustrates the conceptual structure of UAV photogrammetry research in open-pit mining. The framework organizes existing studies into four interconnected domains—data acquisition, data processing, data analysis and modeling, and decision-support applications—while highlighting integration with AI, deep learning, and GIS, as well as emerging trends such as real-time processing and digital-twin systems.

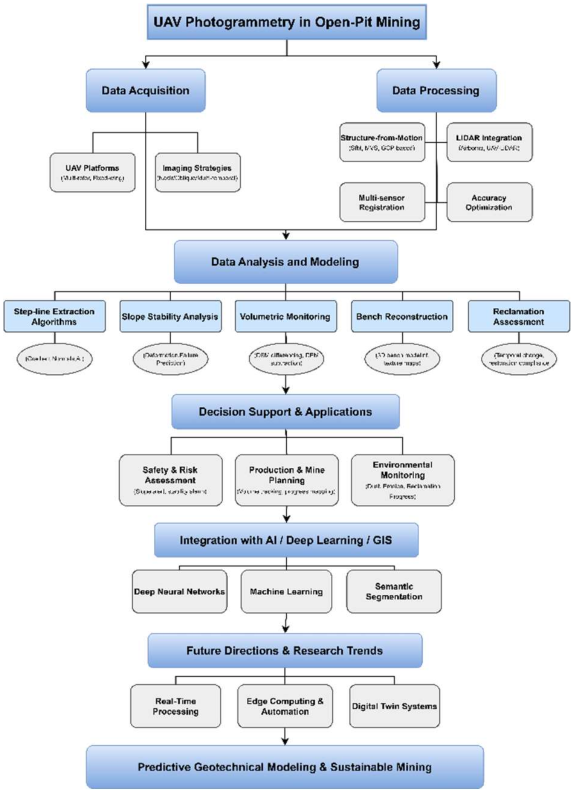

Figure 1. Conceptual framework of UAV photogrammetry in open-pit mining, summarizing the main technological domains, analytical workflows, and research trends identified in reviewed studies.

3. Application Areas of UAV Photogrammetry in Mining

The integration of UAV photogrammetry into mining operations has transformed it from a conventional mapping tool into a cornerstone of modern spatial analytics. It now provides quantitative, repeatable, and cost-efficient solutions for structural modeling, slope safety assessment, and environmental monitoring in open-pit mines. By capturing high-fidelity three-dimensional data across multiple temporal and spatial scales, UAV photogrammetry enhances engineering design, supports operational decision-making, and contributes to sustainable mine management.

This section presents a comprehensive overview of its major application domains, including slope stability assessment, step-line and discontinuity extraction, volumetric analysis, bench reconstruction, and reclamation monitoring, highlighting recent technological advances, accuracy improvements, and implementation challenges in active mining environments.

3.1 Slope Stability Assessment

Slope stability remains one of the most critical aspects of open-pit mine safety. Failures of pit walls or benches can cause significant human, financial, and environmental consequences. UAV photogrammetry, particularly using oblique imagery, provides high-resolution and continuous observations of pit faces, fractures, and fault systems. The derived 3D models allow accurate computation of slope angles, deformation zones, and discontinuity networks.

Numerical simulations integrated with UAV-derived models—such as the finite volume method, the Savage–Hutter flow model, and the GDEM-GAVA numerical simulator—have proven valuable in predicting landslide trajectory, velocity, and mass accumulation. For example, Liu et al. (2024a) simulated the evolution of a large-scale open-pit landslide, identifying two major accumulation zones (upper and mid-step) with an estimated volume exceeding 30,000 m³ (Liu et al., 2024a). Multi-temporal UAV imaging further enables deformation trend analysis and real-time monitoring of high-risk slopes (Tang et al., 2024; Cao et al., 2023). The fusion of UAV data with AI-driven change detection algorithms enhances early-warning capability, marking a transition from static to predictive slope monitoring.

3.2 Step Line and Discontinuity Extraction

Accurate extraction of step lines—representing the boundaries between excavation benches and slope surfaces—is a fundamental prerequisite for geometric modeling and safety analysis in open-pit mining. These structural lines play a key role in bench design, drilling layout, slope management, and overall geotechnical supervision. Traditional field-based surveys for delineating step boundaries are often time-consuming, labor-intensive, and prone to positional errors, particularly under conditions of steep terrain or poor accessibility.

UAV photogrammetry, primarily through Structure-from-Motion (SfM)-derived point clouds, provides a dense and reliable basis for automated step-line extraction. Recent research identifies three principal algorithmic families—each addressing specific challenges related to noise suppression, geometric continuity, and computational scalability.

3.2.1 Gradient-Based Elevation Edge Detection

Wang et al. (2021) introduced an elevation-gradient method using DSM data to identify abrupt height variations corresponding to bench edges. The workflow includes (1) height-differencing to detect discontinuities, (2) application of morphological filters to eliminate outliers, and (3) use of polyline-tracing algorithms to maintain continuity. Field experiments across several open-pit test sites achieved a mean horizontal accuracy better than 15 cm. The technique is computationally efficient and well-suited for quick geometric updates in active mining operations.

3.2.2 Surface Normal and Edge Polarity Analysis

Mao et al. (2022) presented a robust step line extraction technique that relies on analyzing surface normal variations in conjunction with edge polarity indicators. The proposed algorithm operates in four main stages: (1) initial segmentation of the point cloud based on local deviations in surface normal, which helps isolate regions with potential structural features; (2) detection of sharp angular changes that correspond to discontinuities or slope breaks; (3) application of a region growing process to ensure continuity within identified clusters; and (4) implementation of noise filtering mechanisms, leveraging both point density metrics and directional consistency to suppress outliers. The method demonstrated high accuracy and stability when applied to irregular and noisy terrain, making it well-suited for near-real-time deployment in operational open-pit mining environments.

3.2.3 Structural Feature-Based Line Modeling

Cui et al. (2024) proposed a structural feature-driven approach that exploits geometric properties of benches—such as slope angle, growth direction, and relative elevation differences. The method utilizes mesh-based analytical functions and curvature tracking to extract breaklines at structural discontinuities. By incorporating topographic context and geometric validation, the algorithm effectively distinguishes true structural boundaries from pseudo-contours caused by noise or vegetation.

Field tests achieved extraction accuracy exceeding 92% with substantially fewer false positives, while maintaining scalability for large datasets containing over 50 million points. This scalability makes it particularly suited for large open-pit environments where both horizontal and vertical continuity must be preserved.

3.2.4 Summary of Comparative Strengths

The integration of gradient-based, surface-normal, and structural modeling algorithms has established UAV-derived point clouds as a robust and quantitative framework for step-line extraction. Table 1 summarizes their relative strengths, highlighting trade-offs in efficiency, accuracy, and scalability. Hybrid approaches that combine gradient, normal, and structural analyses provide the most balanced performance for real-world mining operations. Integrating these algorithms into mine design software enables automated bench modeling, thereby enhancing slope stability assessment, equipment planning, and volumetric analysis—forming the foundation of intelligent, data-driven mine management.

ALGORITHM TYPE	KEY ADVANTAGE	LIMITATION
GRADIENT-BASED ELEVATION	Fast computation and simplicity	Limited precision in noisy terrain
SURFACE NORMAL + EDGE POLARITY	High geometric accuracy and robustness	Higher computational demand
STRUCTURAL FEATURE MODELING	Scalable and adaptable to large datasets	Requires extensive pre-processing

Table 1. Summary of Comparative Strengths

3.3 Volumetric Monitoring and Stockpile Assessment

Volumetric monitoring is one of the earliest and most widespread applications of UAV photogrammetry in open-pit mining. By comparing DSMs and DEMs from successive UAV flights, height differentials are used to calculate cut-and-fill volumes with sub-3% mean error in most cases. This approach effectively replaces traditional total-station and GNSS-based volume measurements, offering both accuracy and operational speed.

Advanced workflows for complex mine topographies employ pixel-wise elevation differencing, slope-boundary delineation, and morphological filtering to reduce noise near bench edges (Cao et al., 2023; Liu and Tan, 2024). Integration with AI-enhanced algorithms allows automated classification of stockpiles and differentiation of material types. UAV-based volume assessments have been successfully used for production auditing, stockpile management, and backfill verification in both active and reclaimed mining areas (Caihuan and Wendong, 2020; Zhong and Liu, 2025).

3.4 3D Bench Modeling

Benches serve as the fundamental structural and operational units of open-pit mines, influencing slope design, drainage, and equipment access. Accurate 3D reconstruction of benches is therefore essential for optimizing safety and efficiency. UAV photogrammetry, employing precise flight planning and SfM-based modeling, produces high-fidelity mesh models with detailed texturing and metric accuracy suitable for direct use in mine-planning software.

Studies by Lu et al. (2021) and Mao et al. (2022) demonstrate that UAV-derived 3D models accurately capture bench width, height, and inter-bench angles with RMSE below 0.07 m. These models support geometric validation, machinery path design, and redesign of slope configurations. Combined with LiDAR or oblique datasets, UAV photogrammetry provides the geometric input necessary for geomechanical simulations, facilitating realistic stability and drainage analyses (Wierzbicki, 2018; Liu and Tan, 2024).

3.5 Mine Reclamation Monitoring

Environmental reclamation has become a critical requirement of sustainable mining operations. UAV-based photogrammetry provides an efficient framework for dynamic monitoring of post-mining rehabilitation projects. Periodic oblique imaging allows visualization of terrain reshaping, backfilling, and vegetation recovery, while DSM differencing quantifies volumetric progress with accuracy better than 5%.

Zhong and Liu (2025) demonstrated that using UAV oblique datasets with a GSD of 2.5 cm/pixel, it is possible to monitor reclamation over four temporal phases, yielding digital 3D mesh and DLG models that quantify backfill volume (0.017 km^3) and building demolition areas (16,400 m^2). Analytical platforms such as ArcGIS and 3DCASS support automated measurement and visualization of progress (Deng, 2021; Zhong and Liu, 2025). Future developments include UAV–ground station networks for autonomous, continuous reclamation monitoring.

4. Comparative Evaluation of Methods and Technologies

Comparative analysis is essential in interdisciplinary reviews such as UAV-based photogrammetry in mining, where diverse platforms, algorithms, and applications coexist. Organizing this information into structured comparative frameworks enables clearer insight into methodological strengths, operational constraints, and best practices.

This section consolidates findings from over 30 recent studies (2017–2025) into analytical tables covering key domains: (1)

step-line extraction algorithms, (2) UAV application areas, (3) photogrammetric software tools, (4) imaging strategies, (5) volumetric modeling methods, and (6) machine learning techniques. Each table summarizes major characteristics and performance metrics, linking them to practical use cases.

The framework assists researchers and practitioners in selecting appropriate technologies based on accuracy, automation potential, scalability, field adaptability, data requirements, and cost-effectiveness. Overall, this structured comparison bridges the gap between theoretical research and field implementation, fostering more efficient integration of UAV photogrammetry into modern open-pit mine monitoring and spatial analysis.

4.1 Comparison of Step Line Extraction Algorithms

Table 2 provides a comparative overview of the three primary algorithms for extracting step or break lines from UAV-derived point clouds. Evaluation criteria include algorithm type, required input, reported accuracy, noise tolerance, scalability, and computational efficiency. Wang et al. (2021) method emphasizes simplicity and speed through gradient-based edge detection. Mao et al. (2022) focuses on robustness in noisy datasets via surface-normal and polarity analysis. Cui et al. (2024) leverages geometric and structural attributes for high scalability and precision in large datasets.

Collectively, these algorithms demonstrate that the choice of approach depends on project scale, terrain complexity, and accuracy requirements, with hybrid frameworks offering optimal trade-offs between performance and efficiency.

4.2 UAV Application Areas in Mining

Table 3 compares five core application domains of UAV photogrammetry in open-pit mining such as: slope stability monitoring, step-line extraction, volumetric assessment, 3D bench modeling, and reclamation tracking. Each category is analyzed in terms of input data, target output, processing software, reported accuracy, and operational reliability.

The results reveal that volumetric monitoring and reclamation supervision exhibit higher automation and field efficiency, while step-line extraction and bench modeling demand denser point clouds and more complex post-processing workflows. These insights help align UAV deployment strategies with project-specific requirements and operational timelines.

4.3 UAV Photogrammetry Software Tools

Table 4 summarizes the most frequently utilized photogrammetric software tools according to functional capability, input type, analytical features, and operational limitations. Pix4D and Agisoft Metashape dominate high-accuracy 3D reconstruction workflows. Cloud Compare remains indispensable for point-cloud editing and change detection. MATLAB and Python are used extensively for algorithm development, while DJI Terra facilitates rapid modeling within DJI-based ecosystems.

This table enables researchers to align software selection with team expertise, data volume, and desired analytical complexity, ensuring methodological reproducibility and consistency.

STUDY (REF)	ALGORITHM TYPE	INPUT DATA	ACCURACY	NOISE HANDLING	SCALABILITY	EXECUTION TIME	APPLICATION SUITABILITY
WANG ET AL. (2021)	Gradient-based DSM edge detection	DSM from point cloud	<15 cm	Moderate	Medium	Fast	Quick edge extraction, basic benches
MAO ET AL. (2022)	Surface normal + edge polarity + region growing	Raw point cloud	~92% accuracy	High	High	Moderate	Complex terrain, real-time capable
CUI ET AL. (2024)	Structural feature-based modeling (geometry-driven)	Mesh from point cloud	>92% (low FP rate)	Very high	Very High (>50M pts)	Moderate to High	High-res structural modeling, design-focused

Table 2. Comparison of Step Line Extraction Algorithms

APPLICATION DOMAIN	PRIMARY INPUT	MAIN OUTPUT	TYPICAL TOOLS	ACCURACY REPORTED	FIELD ADAPTABILITY
SLOPE STABILITY MONITORING	Oblique UAV imagery + SfM models	Slope angles, deformation zones, instability indicators	GDEM-GAVA, 3DReshaper, ArcGIS	±5–10 cm (depending on slope and image configuration)	High (requires proper oblique capture)
STEP LINE EXTRACTION	Dense point cloud from UAV	Bench breaklines, structural edges	Custom Python/MATLAB scripts, MeshLab	Up to 92% accuracy (Wang et al., 2021; Mao et al., 2022; Cui et al., 2024)	Moderate (requires clean, dense clouds)
VOLUMETRIC CHANGE DETECTION	DSM from repeated UAV surveys	Cut/fill volumes, stockpile mass	Pix4D, Cloud Compare, Excel	<3% volumetric error (Cao et al., 2023; Liu and Tan, 2024)	Very high (automated workflows)
3D BENCH MODELING	UAV mesh + texture data	Bench dimensions, surface profiles	Agisoft, Rhino, QGIS	Sub-decimeter mesh accuracy (Wang et al., 2020; Lu et al., 2021)	Moderate (depends on texture quality)
MINE RECLAMATION MONITORING	Multi-temporal DSM and mesh models	Earthwork tracking, reclamation progress	ArcGIS, 3DCASS, OpenDroneMap	Area change within 5% threshold (Deng, 2021; Zhong and Liu, 2025)	High (multi-date UAV support)

TABLE 3. COMPARISON OF UAV APPLICATION AREAS IN MINING

SOFTWARE	KEY FEATURES	INPUT TYPE	STRENGTHS	LIMITATIONS	CITED STUDIES
PIX4DMAPPER	Automated photogrammetry, volume & orthomosaic generation	UAV imagery	User-friendly, cloud-compatible, accurate DSM	High cost, limited manual editing	(Tong et al., 2015; Wang et al., 2020; Cao et al., 2023)
AGISOFT METASHAPE	Dense 3D model generation, multispectral support, scripting	UAV imagery	Highly customizable, accurate texture mapping	Requires GPU, heavier learning curve	(Mao et al., 2022; Wang et al., 2020; Lu et al., 2021)
CLOUDCOMPARE	Point cloud editing, segmentation, and manual filtering	Point clouds	Free & powerful for manual point analysis	Manual steps, not suited for automation	(Jafari and Dorafshan, 2025; Cao et al., 2023)
MATLAB	Algorithm prototyping, 3D matrix ops, ML integration	Point clouds/mesh	Customizable & scalable, ML module support	Requires coding skills, not specialized	(Jafari and Dorafshan, 2025)
3DRESHAPER	Precise 3D editing, breakline extraction, slope calc	Mesh/ point cloud	Precise slope and feature extraction tools	Commercial license needed, steep UI	(Cui et al., 2024; Wang et al., 2020)
DJI TERRA	Fast terrain modeling, integrated with DJI drones	UAV imagery	Real-time processing, UAV flight integration	Less flexible outside DJI ecosystem	(Hao et al., 2023; Liu and Tan, 2024)

Table 4. Comparison of UAV Photogrammetry Software Tools

4.4 UAV Imaging Strategies

Table 5 compares various UAV imaging configurations, including nadir-only, oblique, hybrid nadir-oblique, multi-temporal imaging, and low-altitude high-resolution capture. It highlights parameters such as flight angle, camera setup, coverage type, accuracy, and ideal applications. Oblique and hybrid strategies are particularly effective for modeling benches and structural slopes. This overview guides aerial mission planning to ensure optimal spatial coverage and 3D reconstruction fidelity.

4.5 Volumetric Modeling Methods

Table 6 compares five different volume estimation techniques using UAV-derived elevation or surface models. These methods vary in terms of input data (DSM, mesh, TIN), reported accuracy, level of automation, and operational feasibility in the field. DSM differencing and DEM subtraction offer high automation, while cross-sectional slicing allows for controlled analysis. This comparative view helps practitioners select a method based on terrain complexity, required resolution, and available software infrastructure.

4.6 Machine Learning Applications in UAV Mining Data

Table 7 analyzes the role of machine learning techniques in UAV-based mining workflows, including CNN, U-Net, K-means, Random Forest, and attention-based models. It highlights input types, target outputs, accuracy levels, and use cases, addressing the classification of slopes, detection of structural features, semantic mapping, and prediction of deformation trends. The table illustrates the growing capabilities of AI to automate and enhance geospatial analysis in mining operations.

IMAGING STRATEGY	FLIGHT ANGLE	CAMERA SETUP	COVERAGE TYPE	ACCURACY LEVEL	RECOMMENDED USE CASES
NADIR-ONLY IMAGING	90° (vertical)	Single vertical sensor	Top surfaces only	Medium (limited depth detail)	Stockpile volume calculation, DEM
OBLIQUE MULTI-ANGLE IMAGING	30°- 60° (angled)	4 sides + one vertical camera	Sidewalls, slopes, and benches	High (structural detail)	Slope monitoring, wall modeling
COMBINED NADIR + OBLIQUE	90°, 30°- 60°	Integrated multi-camera rig	Full 3D structure with reduced blind spots	Very high (optimized geometry)	Geotechnical analysis, bench extraction
MULTI-TEMPORAL IMAGING	Variable over time	Same setup across multiple dates	Surface change analysis	Temporal accuracy varies	Reclamation monitoring, change detection
HIGH-RESOLUTION CLOSE-RANGE UAV FLIGHTS	Low-altitude oblique	High-res gimbal camera	Detailed mapping of small features	Sub-decimeter for features	Crack inspection, localized mapping

Table 5. Comparison of UAV Imaging Strategies

METHOD	INPUT DATA	ACCURACY	AUTOMATION LEVEL	FIELD SUITABILITY	CITED STUDIES
DSM DIFFERENCING	DSM from UAV surveys (multi-epoch)	<3% error (with GCPs)	High (Pix4D, Cloud Compare)	Very high (automated & fast)	(Cao et al., 2023; Liu and Tan, 2024)
CROSS-SECTION ANALYSIS	Mesh slices from 3D model	3 - 5% depending on alignment	Moderate (manual slicing)	Medium (requires human oversight)	(Wang et al., 2020)
MESH VOLUME CALCULATION	Closed mesh from point cloud	2 - 4% (high with sharp mesh)	Moderate to High (Agisoft, MeshLab)	Good for small zones	(Lu et al., 2021)
TIN VOLUME MODELING	TINs generated from a dense point cloud	~5% depending on resolution	High (GIS-based automation)	High for detailed planning	(Qing et al., 2025)
MULTI-TEMPORAL DEM SUBTRACTION	DEM from multiple UAV flights	2 - 6% over large areas	High with pre-aligned data	Ideal for restoration/monitoring	(Deng, 2021; Zhong and Liu, 2025)

Table 6. Comparison of Volumetric Modeling Methods

ML TECHNIQUE	INPUT TYPE	TARGET OUTPUT	REPORTED ACCURACY	USE CASE	REFERENCE
1D-CNN	Point cloud (attributes)	Step line classification	>92%	Bench and slope segmentation	(Jafari and Dorafshan, 2025)
U-NET	Orthophoto + DEM	Semantic segmentation (mining classes)	High (visual agreement)	Ecological restoration mapping	(Cao et al., 2023)
K-MEANS CLUSTERING	3D Point cloud (intensity/geometry)	Point grouping (slope zones)	Moderate, unsupervised	Slope region zoning	(Mao et al., 2022)
RANDOM FOREST	Labeled terrain features	Change detection, vegetation	~88% classification accuracy	Land cover classification	(Deng, 2021)
ATTENTION-BASED CNN (ACNN)	Time-series UAV point clouds	Deformation trend prediction	F1-score > 89%	Predictive slope monitoring	(Cao et al., 2023)

Table 7. Comparison of Machine Learning Applications in UAV Mining Data

5. Challenges and Opportunities in UAV Photogrammetry for Open-Pit Mining

UAV photogrammetry has rapidly evolved into a core technology for data acquisition, modeling, and monitoring in open-pit mining. However, several technical, environmental, and computational challenges continue to constrain its full potential. At the same time, emerging advances in artificial intelligence, sensor fusion, and automation are creating new opportunities to improve efficiency, accuracy, and sustainability in mine monitoring. This section provides an overview of key limitations and future development trends.

5.1 Technical and Operational Challenges

Open-pit mines present demanding conditions for UAV photogrammetry due to their steep geometries, rugged terrain, and variable environmental settings. Imaging of near-vertical or overhanging slopes remains one of the most persistent difficulties, as these geometries restrict line-of-sight visibility and cause occlusions or incomplete data coverage. Although oblique photogrammetry mitigates such issues, it becomes challenging to operate in unstable areas or narrow benches.

Environmental factors—including wind, dust, fog, and uneven illumination—further degrade image quality and increase surface noise, leading to reduced reconstruction accuracy and incomplete structural representation. These effects are particularly pronounced in deep pits where shadows and light reflections distort image consistency.

Multi-temporal monitoring, such as slope deformation or volumetric change analysis, requires precise alignment of datasets from different time periods. Without RTK-enabled georeferencing or sufficient ground control points (GCPs), registration errors may accumulate, producing misleading displacement or volume estimations.

The computational demands of processing dense point clouds—often exceeding tens of millions of points—also pose a significant bottleneck. Without optimized workflows or high-performance computing resources, delays in model generation and analysis are inevitable.

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Another challenge lies in automated feature extraction. Algorithms for identifying step lines, fractures, or semantic regions are sensitive to spatial noise, uneven point density, and texture variability. These factors increase segmentation errors and reduce the reliability of derived geotechnical parameters.

5.2 Emerging Opportunities and Future Directions

Despite these limitations, rapid technological progress presents numerous opportunities to enhance UAV photogrammetry for open-pit mining. The integration of UAV data with AI-driven analytics and GIS platforms is enabling next-generation mining systems capable of automated modeling, real-time monitoring, and predictive decision support.

Deep learning architectures, such as CNN, U-Net, and attention-based models, now deliver higher reliability in fracture identification, slope classification, and early detection of instability zones, significantly reducing manual inspection requirements.

Future UAV systems are expected to incorporate customizable multi-sensor payloads, adaptive cameras, and autonomous flight planning tailored to mining environments—improving both safety and efficiency in confined or hazardous settings.

Long-term time-series UAV datasets will continue to enhance understanding of slope deformation dynamics, reclamation progress, and excavation planning. These datasets support predictive geotechnical modeling, enabling proactive management rather than reactive mitigation.

Finally, the development of fully automated UAV-to-model pipelines promises faster data turnaround, lower operational costs, and greater consistency, establishing UAV photogrammetry as a scalable, intelligent, and indispensable component of modern mine monitoring frameworks.

6. Conclusion and Future Outlook

Over the past decade, UAV-based photogrammetry has evolved from a supplementary mapping technique into a core technological framework for spatial monitoring, structural modeling, and environmental management in open-pit mining. This comprehensive review of more than 30 peer-reviewed studies (2017–2025) demonstrates that the integration of UAV platforms with advanced computational techniques—such as Structure-from-Motion (SfM), oblique multi-angle imaging, deep learning algorithms, and airborne LiDAR—has substantially improved geometric accuracy, operational efficiency, and analytical automation in mining applications.

Quantitative evidence from the reviewed studies indicates that hybrid SfM–AI workflows can achieve horizontal and vertical accuracies of approximately ±2.9 cm and ±6.4 cm, respectively, while maintaining volumetric error rates generally below 5%. Oblique imaging strategies consistently demonstrate superior geometric completeness in steep and structurally complex pit environments, particularly for bench reconstruction, step-line extraction, and slope monitoring. Meanwhile, machine learning approaches increasingly enable automated classification, deformation trend analysis, and predictive modeling, reducing reliance on manual interpretation and improving scalability.

The reviewed applications span critical operational domains, including slope stability assessment, structural discontinuity extraction, volumetric monitoring, 3D bench modeling, and mine reclamation supervision. Although each domain presents specific technical challenges—such as data occlusion, surface noise, multi-temporal misalignment, and high computational demand—the convergence of multi-sensor integration, AI-driven analytics, and cloud-based processing frameworks is steadily mitigating these limitations.

Looking forward, several research priorities emerge. First, the development of fully automated and noise-robust algorithms for structural feature extraction from large-scale point clouds remains essential for improving reliability in complex terrains. Second, long-term multi-temporal UAV datasets should be leveraged to enable predictive geotechnical modeling, facilitating proactive slope risk management rather than reactive mitigation. Third, multi-sensor fusion—combining photogrammetry with LiDAR, multispectral, and thermal sensing—offers significant potential for enhancing both structural and environmental interpretation. Finally, the implementation of real-time or near-real-time UAV-to-model processing pipelines will be crucial for supporting intelligent, autonomous, and safety-critical mine monitoring systems.

In summary, UAV photogrammetry is transitioning from a data acquisition tool to an integrated decision-support platform within open-pit mining. Its continued evolution toward automated, multi-source, and predictive monitoring frameworks positions it as a cornerstone technology for intelligent, high-precision, and sustainable mining operations in the years ahead..

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