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Brief Analysis on Application Advantages of UAV Surveying and Mapping technology in Open-Pit Mines

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Abstract

UAV surveying and mapping technology, leveraging its efficiency, precision, and flexibility, demonstrates significant advantages in open-pit mine resource development, hazard prevention, and ecological restoration. This paper systematically reviews the evolution of UAV surveying and mapping technology, elaborates on its application workflow in open-pit mines, and summarizes nine core advantages. Concurrently, it analyzes challenges including environmental constraints, data processing bottlenecks, and regulatory gaps. Future directions are proposed across three dimensions: technological breakthroughs, application expansion, and cross-sector collaboration. By establishing a dynamic equilibrium mechanism for exploration-extraction-reclamation, UAV surveying catalyzes digital and intelligent transformation in open-pit mining, delivering innovative solutions for sustainable mineral industry development.

Keywords: advantages, applications, open-pit mines, UAV surveying and mapping technology

1. Introduction

The exploitation and utilization of mineral resources have provided crucial support for China’s economic development. However, while driving industrialization, mining activities have also significantly impacted geological environments in and around mining areas[1]. Particularly in large-scale open-pit mining, direct topographical alteration and rock mass fragmentation readily trigger geological hazards such as rockfalls, landslides, and unstable rock masses, endangering lives and property. Against this backdrop, establishing a precision dynamic monitoring system has become essential for sustainable open-pit mining operations

Utilizing high-precision drone surveying technology to obtain 3D terrain data, disaster risk point distribution, and resource volume changes in mines not only provides decision-making support for mine safety production but also establishes the data foundation for geological environment remediation efforts such as slope management and ecological restoration. Compared to traditional manual surveying—which faces limitations like low efficiency, high costs, and difficulty covering high-risk areas—drone surveying demonstrates significant advantages: higher efficiency, flexibility, high data accuracy, lower costs, safety, environmental friendliness, and adaptability to complex terrains. This technology enables millimeter-level deformation monitoring and early warning for hazards like surface fractures and slope displacement. This integrated "space-air-ground" intelligent monitoring model forms a complete closed loop for open-pit mine resource development, disaster prevention, and ecological restoration. The technology not only drives the digital and intelligent transformation of open-pit mining production but also provides innovative technical solutions for green mineral resource development. By establishing a dynamic balance mechanism for "exploration-exploitation-reclamation", it strongly supports sustainable development strategies in the mining industry.

2. The Development Process of UAV Surveying and Mapping Technology

UAV-based photogrammetry technology constitutes a spatial information acquisition system that integrates an unmanned aerial vehicle (UAV) as an aerial platform with multiple technologies, including remote sensing sensors, the Global Navigation Satellite System (GNSS), Inertial Measurement Units (IMU), and Geographic Information Systems (GIS). Its core principle involves deploying UAVs equipped with high-precision sensors to dynamically capture the spatial coordinates, morphological characteristics, and attribute data of natural geographical features and man-made structures on the Earth's surface. Through algorithmic analysis, including point cloud processing, image stitching, and 3D modeling, this process ultimately generates millimeter-level precision outputs such as Digital Elevation Models (DEM), Digital Orthophoto Maps (DOM), and real-scene 3D models[2].

The evolution of UAV-based photogrammetry technology has progressed from early experimentation to intelligent applications. Its development trajectory can be categorized into distinct phases: the Early Conceptualization and Experimentation Phase, the Initial Application and Military-Dominated Phase, the Civilian Adoption and Technological Advancement Phase, the Widespread Popularization and High-Precision Development Phase, and the Intelligentization and Multi-domain Integration Phase(Table 1). Each phase is characterized by unique technological features, application domains, advantages, and limitations.

Table 1. Evolution of Drone Surveying and mapping technology

Phase	Technical features	Application domains	Advantages	Limitations
Early conceptual and experimental phase (early 20th century to 1980s)	Initial use of radio-controlled model aircraft carrying film cameras for aerial photography Navigation via manual control; data processing using traditional photogrammetric techniques.	It is limited to scientific research and small-scale topographic mapping experiments.	Pioneering significance: Established foundational concepts of drones as aerial platforms. Low cost: Lower initial experimental expenses compared to manned aircraft.	Technical constraints: No autonomous navigation, low accuracy (meter-level errors), Short endurance (only tens of minutes). Operational complexity: Required specialized operators, Data post-processing took weeks. Application restrictions: Only viable for small-scale trials, not scalable for widespread implementation.
Initial application and military dominance phase (1980s to 2000)	Integration of GPS technology improving positioning accuracy (sub-meter level), Military drones equipped with high-resolution sensors, Preliminary automation of flight control systems.	Military reconnaissance, battlefield mapping, and basic geographic data collection in select countries.	Enhanced accuracy: GPS reduced positioning errors to sub-meter level. Initial automation: Basic implementation of flight path planning and autonomous flight. Military value: Provided real-time mapping support for complex terrain battlefields.	High costs: Military-grade equipment exceeded $1 million per unit, hindering civilian adoption. Policy restrictions: Technology monopolized by military, limiting civilian applications. Endurance bottleneck: Power limitations of battery/fuel systems capped operations at 1-2 hours.
Civilian adoption and technological advancement phase (2000 to 2010)	The rise of consumer-grade multirotor UAVs (e.g., early DJI models), Proliferation of digital cameras and LiDAR (Light Detection and Ranging), Full automation of flight control software.	Disaster assessment, agricultural monitoring, urban planning.	Cost reduction: Civilian drones became affordable (thousands of USD). Operational simplicity: Automation enabled operation by non-specialists. Data diversification: Supported multi-source data collection (visible light, IR, LiDAR).	Accuracy limitations: Without RTK technology, horizontal accuracy remained at 1-3m. Processing constraints: Reliance on desktop platforms (e.g., Pix4D) with slow processing speeds. Regulatory gaps: Incomplete airspace management policies led to widespread unauthorized flights.
Popularization and high-precision development	RTK and PPK technologies achieving centimeter-level	Smart city development, real estate registration,	High precision: Horizontal accuracy 2-5 cm, Vertical accuracy 1-3 cm.	Airspace conflicts: Urban airspace congestion requiring flight permits. Endurance barrier:

phase (2010 to 2020)	positioning accuracy, Oblique photogrammetry enabling real-scene 3D modeling, Cloud computing accelerating data processing.	BIM-integrated engineering supervision, mine surveying, etc.	Efficient modeling: Square-kilometer-scale 3D models generated within 72 hours. Scalable deployment: Enterprise-grade UAVs (e.g., DJI series) widely adopted.	Multirotor flight time still <30 minutes. Specialization threshold: Demanded geomatics expertise for point cloud/model processing.
Intelligent and Multi-domain Integration phase (2020 to now)	Artificial intelligence (AI) algorithms enabling automatic feature extraction, Real-time data transmission via 5G networks, Coordinated mapping through UAV fleet systems.	Environmental monitoring (e.g., carbon neutrality assessment), emergency disaster response (real-time hazard modeling), digital twin construction.	Intelligent analysis: AI automates extraction of roads/buildings with 70% efficiency gain. Cross-technology integration: Synchronization with IoT sensors and satellite data. Autonomous operation: Obstacle avoidance and dynamic path adjustment capabilities.	Privacy controversies: High-precision mapping raises data leakage risks. Security vulnerabilities: Potential fleet system hijacking through cyberattacks. Regulatory lag: Existing policies fail to govern BVLOS (Beyond Visual Line of Sight) operations.

3. UAV Surveying Workflow

UAV surveying employs aerial photogrammetry, commencing with comprehensive indoor preparatory work. This is followed by UAV aerial photography to acquire original image data of the survey area, supplemented by photogrammetric control point data collected via RTK measurements. The acquired data undergoes 3D reality mesh reconstruction using Smart3D software. Subsequently, the Cass3D mapping platform loads the generated 3D model to produce Digital Line Graphics (DLG)[3].

3.1 Preliminary Preparation

Initial preparations involve defining project objectives for open-pit mining applications, such as resource estimation, earthwork volume calculation, slope deformation monitoring, and geohazard investigation, and establishing critical survey parameters including the mine's coordinate system, vertical datum, map scale, topographic sheet layout, and aerial photography specifications. Equipment selection is determined by terrain complexity: LiDAR-equipped UAVs (e.g., DJI L1) are deployed for rugged topography, while multi-rotor platforms with oblique photogrammetry capabilities (e.g., Phantom 4 RTK) suffice for routine monitoring operations.

3.2 Data Acquisition

The pre-placement of photogrammetric control points (PCPs) is typically designed using satellite imagery, adhering to the principles of "corner-point placement, intermediate densification, and uniform distribution." During field operations in mining areas, pre-designed points are staked out using mobile device positioning, with subsequent adjustments made based on ground reconnaissance.

PCP measurements are conducted using Real-Time Kinematic (RTK) technology to simultaneously capture planimetric coordinates and elevations[4]. During measurement, a fixed tripod-mounted GPS rover station is deployed. Observations are recorded with a minimum of 20 valid satellites tracked per session, and each point is measured for no fewer than three observation cycles. The final coordinates are derived from the average of these repeated measurements.

Aerial photogrammetry commences with flight path planning, followed by UAV deployment at designated mining area locations. Upon takeoff, flight control software assumes autonomous operation while continuously monitoring flight attitudes. The UAV returns immediately if anomalies are detected. Post-flight quality assessments are performed without delay, evaluating vertical image alignment, flight path curvature, and altitude consistency. Image quality undergoes rigorous indoor inspection through a dual approach combining software analysis and manual verification to ensure data integrity.

3.3 Data Processing

Three-dimensional modeling is performed using the reality modeling system (Smart3D) through the following workflow: data preparation—including original aerial images, sensor parameters, POS data, and photogrammetric control point data—is imported into the modeling system; followed by aerial triangulation computation; model partitioning and reconstruction; and final 3D model output (Figure.1). Office-based stereoscopic mapping employs the CASS3D mapping system for data acquisition, which involves creating DWG files, loading oblique models and orthoimagery, performing data editing and processing, conducting quality checks, and exporting final data products (Figure.2). Topographic map editing primarily utilizes the spatial measurement capabilities of the CASS3D stereoscopic mapping system, enabling direct extraction of terrain features, cultural objects, and landforms from the 3D reality model. Field verification plots overlaid with imagery are used for qualitative field supplementation, with all annotated features inked onto the verification plots for subsequent computer-aided editing. Data organization and refinement are executed in accordance with cartographic specifications and project requirements, using the CASS3D-collected data as the foundation while referencing field annotation results[5].

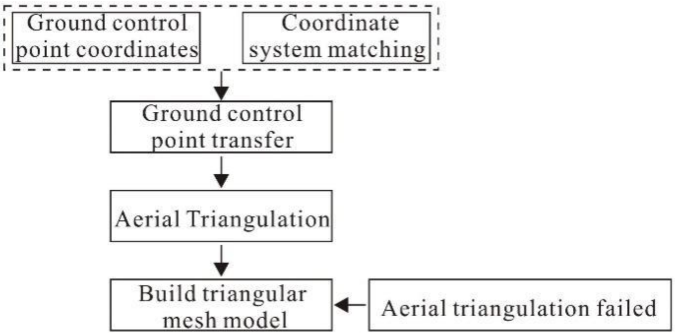

Figure 1. Flowchart of Real Scene 3D Modeling

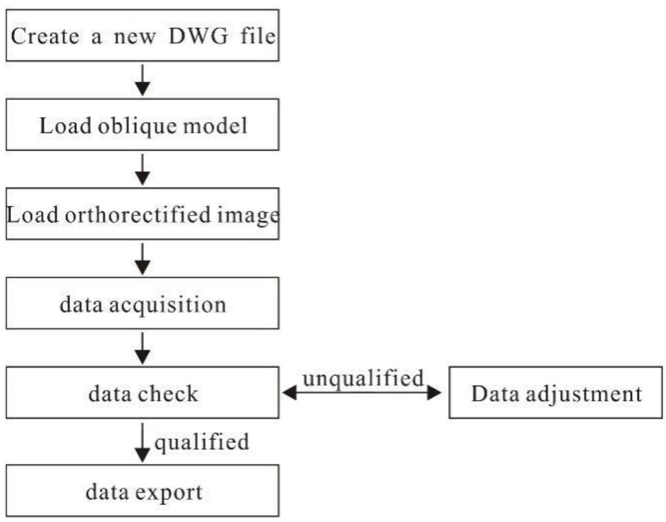

Figure 2. Flowchart of CASS3D 3D Stereoplotting

3.4 Output of Results

Standardized UAV surveying deliverables encompass five core data products: Digital Orthophoto Maps (DOM), Digital Surface Models (DSM), platform-integratable 3D visualization assets, OpenSceneGraph binary (OSGB) format models, and point cloud data[6].

4. Application Advantages of UAV Surveying and Mapping Technology in Open-Pit Mine

4.1 Efficient Operation Capability

UAV surveying significantly enhances operational efficiency through automated flight and rapid data acquisition, enabling extensive area coverage at rates of dozens of square kilometers per hour in field operations (using multi-rotor or fixed-wing platforms). This far exceeds traditional manual surveying methods. Following predefined flight paths, UAVs autonomously collect data with minimal human intervention, making them particularly suitable for complex topographies, landform investigations, and geological hazard assessments in open-pit mines. Practical applications across multiple mines demonstrate UAV efficiency at 15 to 25 times that of manual surveys. For example, in topographic surveying of a limestone quarry covering 0.5 km^2, traditional total station methods required three personnel over six days, whereas UAVs completed the task with two personnel in half a day—an 18-fold efficiency gain. In annual mineral reserve reporting, the cycle for calculating resource consumption was reduced from 6–8 days to 2–3 days. Daily monitoring of open-pit mine slopes during rainy seasons enables rapid early warnings for hazards like rockfalls, landslides, and unstable rocks..

4.2 Be Flexible

UAVs offer exceptional mobility and adaptability to the complex, dynamic environments of open-pit mines, particularly in karst regions with obstructed sightlines, steep slopes, and multiple obstacles. Their modular design allows sensor switching (e.g., visible light → thermal imaging → LiDAR) within five minutes, supporting diverse applications including slope monitoring, equipment inspection, and fire detection. During geological emergencies such as slope failures or landslides, UAVs swiftly capture real-time imagery to inform rescue operations. Their operational flexibility is further enhanced by simplified takeoff/landing without dedicated runways—some compact models even support hand launches—proving invaluable in challenging mine terrains. UAVs maintain stable flight with a lateral deviation within 1.2 meters even under strong winds of 5–6 magnitude.

4.3 High Data Accuracy

Equipped with RTK (Real-Time Kinematic) or PPK (Post-Processed Kinematic) modules[7], UAVs achieve millimeter-level positioning accuracy. In open-pit mine topographic surveys, this technology limits resource estimation errors to within 1% based on captured terrain data. Multi-sensor integration further enhances precision: LiDAR penetrates vegetation to generate high-accuracy terrain models, while oblique photogrammetry enables detailed 3D reality modeling. These capabilities prove invaluable for slope stability assessments and hazardous rock investigations in mining environments.

4.4 Enhanced Safety and Risk Mitigation

UAV surveying eliminates personnel exposure to hazardous zones such as steep slopes and blast areas, substantially reducing operational risks. Advanced obstacle avoidance systems-incorporating radar, visual sensors, and infrared detection (e.g., DJI M300)-identify threats like wire ropes ≥0.5mm diameter at 30-meter ranges, preventing collisions with mining cableways. Industry statistics confirm a 94% reduction in surveying accidents following UAV implementation.

4.5 Cost Efficiency

UAV technology delivers significant cost savings across three dimensions. (1) Hardware investment: Professional UAV kits with LiDAR (¥500,000 to 600,000 ≈ $69,000 to 83,000) represent merely 12.5 to 15% of airborne laser scanning system costs (¥4 million ≈ $550,000), and are substantially more economical than manned aircraft or satellite services. (2) Labor reduction: Missions require only two personnel (pilot + data processor) versus traditional eight-member survey teams, cutting labor costs by 75% while minimizing travel expenses for remote mine sites. (3) Long-term savings: Annual maintenance costs (<¥30,000 ≈ $4,100) undercut total station calibration and prism replacement expenditures (¥80,000 to 120,000 ≈ $11,000 to 16,500). Studies demonstrate 68% reduction in comprehensive surveying costs with investment payback periods under eight months.

4.6 Multidimensional Data Support for Diverse Applications

UAV surveying enables multisource data acquisition, generating high-precision orthophotos, 3D models, topographic maps, and vegetation coverage analyses that accurately reconstruct open-pit mine terrains for reserve calculations and mining strategy formulation. Multispectral sensors assess soil composition and vegetation coverage to evaluate ecological restoration effectiveness, while thermal imaging detects equipment overheating and concealed leaks to prevent fire hazards. Synthetic Aperture Radar (SAR) penetrates cloud cover for surface deformation monitoring, and oblique photogrammetry constructs reality-based models for slope structural analysis. This integrated approach facilitates real-time slope displacement tracking and historical data-driven risk assessment of rockfalls, landslides, enabling preemptive evacuation of personnel and machinery from hazardous zones.

4.7 Environmental Sustainability

UAV surveying aligns with eco-friendly mining initiatives through three key advantages: minimal emissions-electric UAVs consume merely 2 to 3 kWh per mission, reducing CO_2 emissions by 12 kg compared to fuelpowered survey vehicles (per 10 km² coverage); ecosystem protection—non-contact surveying prevents surface damage in fragile areas like reclamation zones, with documented cases showing 98% reduction in ground disturbance during limestone quarry rehabilitation projects; and noise control—multi-rotor UAVs operate below 75 dB(A), significantly lower than blasting (110 dB) or mining trucks. Compliance with international standards is demonstrated by DJI UAVs achieving EU CE noise certification (<77 dB) under ISO 3744 protocols.

4.8 Real-Time Processing and Intelligent Analysis

UAV technology overcomes the latency of traditional surveying through onboard computing modules and 5G transmission, generating 3D models within 10 minutes of data acquisition. This enables daily extraction progress management and supports immediate production decisions in mining operations. Routine UAV patrols capture high-frequency data with millimeter-level accuracy (>95%) in detecting slope displacement and rock fracture propagation, significantly outperforming manual inspections. AI-driven comparison of multi-temporal point cloud data dynamically updates mineral resource estimates while maintaining errors below 3%, substantially reducing human estimation bias.

4.9 Adaptability to Complex Terrains and Specialized Requirements

UAVs transcend the topographic limitations of conventional surveying equipment. Oblique photogrammetry acquires complete texture data from slopes exceeding 85°, while LiDAR penetrates vegetation cover to monitor concealed fractures-resolving limitations of optical photography. Advanced systems dynamically avoid obstacles through real-time recognition of haul trucks and automatic flight path adjustments. Industrial-grade UAVs operate reliably in extreme conditions (-20°C to 50°C / -4°F to 122°F) with wind resistance up to Beaufort scale 7. Field demonstrations, such as XAG UAVs completing missions in Gobi mining areas amid Level-8 gusts, confirm trajectory deviations under 1 meter.

5. Main Challenges and Future Prospects of UAV Surveying

5.1 Major Challenges

While drone surveying technology demonstrates significant advantages in open-pit mining applications, its practical implementation still faces multiple challenges, primarily manifested in the following aspects: (1) Technical limitations in complex environments, adverse weather conditions, electromagnetic interference, and signal obstruction compromise positioning accuracy, while adaptability to complex terrain remains inadequate. (2) Bottlenecks in data processing and analysis, these include the pressure of real-time processing for massive datasets, the complexity of multi-source data fusion, and insufficient generalization capability of AI models. (3) Lagging regulations and standardization, the key issues encompass airspace management constraints, data security and privacy risks, and ambiguous operational qualification requirements and liability delineation. (4) Tension between economic viability and sustainability, the challenges involve high initial investment and maintenance costs, bottlenecks in battery endurance limiting operational efficiency, and pressure from rapid technological obsolescence and upgrade cycles.

5.2 Future Prospects

The evolution of drone surveying technology will primarily revolve around three interconnected trajectories: technological breakthroughs, application expansion, and collaborative ecosystem development. Key advancements will target enhanced anti-jamming capabilities and system adaptability, sophisticated intelligent algorithms with greater computing power, and extended endurance through next-generation energy solutions. Application scenarios will deepen through comprehensive digital mine lifecycle management "exploration-extraction-reclamation", strengthened environmental and social responsibility frameworks, and innovations in drone-enabled emergency response and insurance systems. Concurrently, industry-wide collaboration will drive standardization and policy implementation, shared-economy business models, and refined talent development pipelines to support sustainable sectoral growth.

6. Conclusion

This study examines the developmental trajectory, operational workflows, and advantages of drone surveying technology, yielding the following key conclusions:

(1) In open-pit mining applications, drone surveying enables high-efficiency data acquisition, millimeter-level precision monitoring, and substantial economic benefits. Its environmentally friendly nature, coupled with multi-source data fusion capabilities and adaptability to complex terrains, significantly enhances resource management, disaster early-warning systems, and ecological restoration.

(2) Critical challenges requiring resolution include improving environmental resilience, advancing data processing efficiency, extending battery endurance, refining airspace management regulations, strengthening data security policies, and promoting technical standardization with cross-sector collaborative implementation.

(3) Future advancements-through optimized AI algorithms, 5G real-time transmission, and swarm coordination-will deepen drone surveying's integration into full mine lifecycle management, strengthen emergency response and ecological accountability, and ultimately contribute to intelligent and sustainable mining practices.

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