iJETRM
International Journal of Engineering Technology Research & Management
(IJETRM)
https://ijetrm.com/

LEVERAGING MULTISPECTRAL DRONE IMAGING TECHNOLOGIES FOR MONITORING OPEN-PIT MINES AND IMPROVING PRODUCTION EFFICIENCY

Lukman A. Alabede[1*], Samuel Mohammed Maimako[1] and Joel Mintah Opoku[2]
[1]University of Jos, Nigeria
[2]Altair UAV Technologies, Kwame Nkurumah University of Science and Technology, Kumasi, Ghana

ABSTRACT
Multispectral drone imaging has emerged as a transformative tool in modern open-pit mining, offering a powerful means of capturing high-resolution spatial, spectral, and environmental data at unprecedented scales and frequencies. At a broad level, the technology enables mining operations to transition from periodic manual surveys to continuous, data-rich monitoring, creating a foundation for more predictive, automated, and efficient resource management. By capturing reflectance values across visible and near-infrared bands, multispectral sensors provide detailed insights into surface composition, moisture distribution, vegetation stress, and material differentiation information that conventional optical imaging alone cannot deliver. This broader analytical capability supports environmental compliance, land-rehabilitation planning, and early detection of geotechnical risks such as slope weakening or excessive water accumulation. Narrowing to direct production outcomes, multispectral drone imaging strengthens operational efficiency through precise monitoring of haul roads, ore stockpiles, pit-floor conditions, and blast impact zones. The spectral data allows operators to distinguish ore from waste with higher accuracy, optimize dig-line placement, and reduce misclassification errors that drive unnecessary hauling and processing costs. Moisture and thermal variations captured through multispectral signatures can reveal unstable areas and inform scheduling decisions for excavation, machinery deployment, and haul-road maintenance. Integrating multispectral datasets with mine-planning software, digital twins, and automated dispatch systems further enhances production efficiency. Machine-learning models trained on spectral patterns can predict ore quality, fragmentation outcomes, and equipment performance impacts long before problems occur. Ultimately, multispectral drone imaging provides a scalable, non-intrusive monitoring framework that enhances situational awareness, improves operational precision, and enables mining enterprises to make smarter, data-driven decisions that boost productivity while reducing risks and operational costs.

Keywords:
Multispectral imaging, drone monitoring, open-pit mining, production efficiency, geotechnical analysis, digital twin systems

1. INTRODUCTION

1.1 Background and Importance of Advanced Monitoring in Open-Pit Mines

Open-pit mines operate within highly dynamic geological and operational environments where safety, productivity, and cost-efficiency depend on continuous and accurate monitoring systems [1]. As excavation progresses, bench geometries, slope conditions, haul-road integrity, and blasting zones evolve rapidly, creating conditions that require frequent reassessment to prevent hazardous events such as slope failures or unexpected fragmentation outcomes [2]. Traditional inspection methods often struggle to keep pace with these rapid changes. Advanced monitoring technologies, particularly drone-based sensing, allow engineers to capture high-resolution spatial, spectral, and thermal data across wide areas in significantly less time [3]. These datasets enhance decision-making by providing detailed terrain models and real-time operational insights that support proactive hazard mitigation [4]. In addition, modern monitoring approaches contribute to resource optimization by improving blast design accuracy, material classification, and haul-road performance tracking, ultimately strengthening operational planning [5]. As open-pit mines become deeper and more complex, advanced monitoring serves as a foundational element for maintaining safe and efficient production.

1.2 Limitations of Traditional Geological and Operational Monitoring

Conventional monitoring approaches such as ground surveys, manual geological mapping, and fixed-position sensors remain valuable but exhibit significant limitations when applied to rapidly evolving open-pit environments

iJETRM
International Journal of Engineering Technology Research & Management
(IJETRM)
https://ijetrm.com/

[6]. Manual surveys are labor-intensive, prone to measurement inconsistencies, and expose personnel to unstable slopes and heavy machinery zones [2]. Fixed sensors, including prisms and extensometers, offer accurate point-based measurements but lack the spatial coverage required to capture broad-scale deformation patterns [5]. Furthermore, these instruments cannot easily adapt to newly excavated areas or shifting operational priorities, leading to gaps in situational awareness. Satellite imagery, although useful, often suffers from low temporal resolution and atmospheric interference that restrict its application for day-to-day operational decisions [7]. These constraints hinder the ability of mine operators to detect emerging instabilities, monitor blast progression, or evaluate haul-road conditions in real time. As mining operations expand in depth and size, the limitations of traditional monitoring underscore the need for more agile and comprehensive sensing solutions [8].

1.3 Emergence of Multispectral Drone Imaging Technologies

Multispectral drone imaging has emerged as a transformative solution capable of addressing long-standing monitoring challenges in open-pit mines. By capturing reflectance data across multiple wavelength bands, drones can detect mineralogical variations, moisture gradients, and early signs of slope distress that may not be visible through conventional RGB imaging [9]. These systems provide rapid, repeatable coverage of large areas, enabling continuous updates to geological models and operational maps [10]. Combined with advanced analytics, multispectral datasets support more accurate material classification, improved blast planning, and early hazard detection, making them an essential component of modern open-pit mine monitoring frameworks [1].

2. TECHNICAL FOUNDATIONS OF MULTISPECTRAL DRONE IMAGING

2.1 Principles of Multispectral Sensing in Mining Contexts

Multispectral sensing provides a powerful analytical framework for monitoring geological, structural, and operational conditions in open-pit mines, where spatial and material variability strongly influences production outcomes. By capturing reflected energy across selected wavelength bands, multispectral sensors reveal mineralogical differences, weathering stages, and moisture gradients that are otherwise invisible to traditional RGB cameras [6]. These capabilities are critical in mines where subtle changes in surface composition can indicate altered rock strength, instability risks, or the presence of ore-bearing zones. The underlying principle relies on measuring how different materials absorb, transmit, and reflect electromagnetic radiation, producing unique spectral signatures [9]. When mounted on drones, multispectral sensors deliver high-frequency coverage of benches, haul roads, stockpiles, and pit walls, supporting both geological interpretation and operational planning. Their ability to detect pre-failure surface anomalies strengthens slope-stability monitoring programs and enhances hazard mitigation strategies [11]. Moreover, multispectral data complement LiDAR and photogrammetry outputs by adding spectral richness that enriches classification accuracy. As mining operations expand in scale and complexity, multispectral sensing provides a robust, repeatable, and data-driven foundation for environmental diagnostics, fragmentation prediction, and ore-tracking workflows. Its integration with machine learning and GIS systems further amplifies the interpretive value of spectral signatures, enabling automated detection of materials and conditions relevant to long-term mine planning [14].

2.1.1 Spectral Bands Relevant to Mining

Mining applications commonly rely on visible, near-infrared, and shortwave-infrared bands due to their capacity to discriminate between geological materials with distinct reflectance signatures [7]. Visible bands support color-based interpretation, while near-infrared enables detection of moisture variations and altered rock surfaces. Shortwave-infrared bands are particularly useful for identifying clay minerals, carbonate-rich ores, and oxidized materials associated with weathering zones [15]. These spectral bands allow drones to produce mineral maps, lithological boundaries, and moisture-distribution models that enhance ore-control strategies. Their combined use significantly improves classification performance in environments with high compositional heterogeneity.

2.1.2 Surface Reflectance and Material Interaction

Surface reflectance represents the proportion of incident radiation reflected by a material and forms the basis of multispectral interpretation. In open-pit mines, reflectance varies with mineralogy, grain size, moisture content, and oxidation state, allowing differential identification of geological features [10]. When electromagnetic radiation interacts with a surface, absorption occurs at wavelengths corresponding to specific chemical bonds, while reflection dominates in regions where those bonds are inactive. This interaction generates distinctive spectral curves used to classify materials under varying environmental conditions. For example, iron-rich rocks exhibit strong absorption in visible bands but high reflectance in near-infrared regions, enabling detection of

iJETRM
International Journal of Engineering Technology Research & Management
(IJETRM)
https://ijetrm.com/

altered zones or weathered formations [16]. Moisture similarly reduces reflectance in near-infrared wavelengths, contributing to early identification of water seepage and slope-instability precursors. By quantifying these interactions, multispectral sensors provide a robust method for evaluating geotechnical and compositional variability across evolving terrain surfaces [12].

2.2 Drone Platforms and Sensor Payload Configurations for Open-Pit Mines

Selecting appropriate drone platforms and payload configurations is essential for maximizing multispectral data quality in open-pit mines. Different mining scenarios demand varied flight endurance, maneuverability, and sensing capabilities. Multispectral systems must be integrated into platforms capable of flying safely in dusty, turbulent, and geometrically constrained areas typical of active excavation zones [9]. Payload selection involves balancing sensor resolution, bandwidth coverage, weight, and onboard processing capabilities, ensuring optimal performance without compromising flight stability. High-resolution multispectral cameras combined with inertial measurement units and GNSS receivers enhance spatial accuracy during mapping missions [13]. Environmental conditions such as sun angle, wind variability, and dust density also shape payload design and deployment strategies. Ruggedized sensors and vibration-dampened mounts are especially critical in mines where airflow disruptions from equipment and walls can affect image clarity [6]. Flexible payload modules further enable operators to pair multispectral systems with LiDAR, thermal cameras, or RGB sensors, creating hybrid mapping solutions that improve geological interpretation and operational diagnostics [14]. As mines adopt autonomous drone workflows, payload configurations increasingly rely on real-time onboard processing, enabling immediate spectral analysis for material classification, slope assessment, and hazard detection [11].

2.2.1 Fixed-Wing vs. Multirotor Drone Suitability

Fixed-wing drones are well suited for large open-pit areas requiring long flight endurance, high coverage rates, and efficient acquisition of multispectral datasets across expansive benches or stockpiles [15]. Their aerodynamic design supports extended missions with minimal power consumption, though they struggle in confined or steeply terraced zones. Multirotor platforms, however, excel in maneuverability, vertical takeoff capability, and stability during low-altitude flights near pit walls and active equipment [8]. They allow precise hovering for detailed spectral sampling and are ideal for surveying small benches, fault zones, or localized instability features. Their flexibility makes multirotors the preferred choice for high-resolution, terrain-adaptive multispectral missions in complex pits.

2.2.2 Sensor Calibration and Environmental Adaptation

Accurate multispectral measurements require systematic calibration to ensure reflectance values remain consistent across changing environmental conditions [7]. Calibration procedures include radiometric correction, white-panel referencing, and dark-signal subtraction to reduce noise from sensor drift or lighting variability. In open-pit mines, dust, shadows, and rapid illumination changes present substantial challenges, making pre-flight and mid-mission calibration essential [12]. Environmental adaptation strategies such as adjusting exposure settings, optimizing flight timing, and incorporating atmospheric-correction models further improve spectral integrity. Temperature fluctuations can also affect sensor performance, necessitating thermal stabilization mechanisms [6]. Together, these measures ensure that multispectral datasets remain reliable for material classification and geotechnical interpretation.

2.3 Data Acquisition Protocols and Geospatial Accuracy Considerations

Robust data-acquisition workflows are vital for producing accurate multispectral maps that support geological interpretation, slope-stability monitoring, and operational decision-making in open-pit mines. Data quality depends heavily on flight configuration, sensor calibration, georeferencing routines, and environmental conditions encountered during the mission [11]. High-overlap imaging, terrain-adaptive flight paths, and consistent illumination conditions help reduce radiometric inconsistencies across image sets [14]. Positioning accuracy is maintained through GNSS-integration with inertial measurements, allowing the system to correct for drift and platform motion [10]. Spatial precision becomes particularly important in mines with steep benches and rapidly changing geometries where small reflectance variations may correspond to significant geological or structural implications [16]. Effective acquisition protocols also incorporate redundant passes over critical features to enhance classification certainty and improve reflectance modelling under variable light conditions [8].

2.3.1 Flight Path Planning and Terrain Constraints

iJETRM
International Journal of Engineering Technology Research & Management
(IJETRM)
https://ijetrm.com/

Flight path planning in open-pit mines must account for bench geometry, pit depth, equipment movement, and atmospheric disturbances. Terrain-following flight modes enable drones to maintain constant altitude relative to the surface, ensuring consistent ground-sampling distance and radiometric uniformity [9]. High-overlap frontlap and sidelap configurations support robust mosaicking and spectral correction during post-processing [13]. Operators must also avoid hazardous turbulence zones near high walls, haul roads, or active blasting areas. Dust plumes and shadowed regions require adaptive re-flights to ensure complete coverage and accurate reflectance retrieval [6].

2.3.2 Georeferencing, Orthorectification, and Error Correction

Georeferencing ensures that multispectral imagery aligns accurately with ground coordinates, forming the basis for spatial analysis in mining applications. High-precision GNSS receivers, combined with inertial data, support direct georeferencing, minimizing dependence on ground control points in difficult-to-access areas [12]. Orthorectification corrects terrain distortions caused by steep benches and elevation changes, producing uniform, map-ready datasets suitable for geological interpretation [14]. Error-correction routines including bundle adjustment, atmospheric compensation, and reflectance normalization further enhance spatial and radiometric accuracy [15]. These steps reduce positional drift and illumination variability, ensuring that material classification, moisture detection, and instability monitoring remain reliable across diverse pit environments [16].

3. OPERATIONAL MONITORING APPLICATIONS IN OPEN-PIT MINES

3.1 Haul Road Condition Monitoring and Traffic Optimization

Efficient haul-road management is critical in open-pit mining, where truck performance, fuel consumption, and tire longevity depend heavily on road surface quality and geometric consistency. Multispectral drone imaging enhances conventional inspection methods by enabling continuous, spatially comprehensive monitoring of haul-road integrity under varying operational conditions [14]. High-frequency overflights produce detailed reflectance maps that reveal moisture accumulation, rutting progression, and surface deterioration with far greater precision than manual surveys. These data layers feed directly into mine-fleet management systems, where optimized haul-route assignments can reduce travel time, enhance safety, and support predictive maintenance strategies [17]. By integrating spectral indices with elevation models, operators can identify underperforming road sections contributing to excessive fuel burn or reduced truck cycle efficiency. Variations in road surface composition or compaction can be rapidly highlighted through reflectance anomalies, facilitating targeted road repairs before conditions degrade further [20]. In high-traffic zones, multispectral imaging helps quantify the impacts of dynamic loads on structural wear, linking spectral patterns to mechanical stress behaviors. The ability to monitor haul-road conditions consistently across wide pit areas strengthens decision-making around truck scheduling, road-watering protocols, and dust-suppression plans [22]. Ultimately, multispectral drone data enable a proactive, data-rich approach to traffic optimization, reducing operational delays and enhancing overall productivity [24].

3.1.1 Moisture Detection and Rutting Assessment

Moisture is a primary driver of rutting and structural deformation on haul roads, especially in pits with variable groundwater conditions or aggressive watering practices. Multispectral sensors capture near-infrared reflectance reductions that correspond to elevated moisture levels, enabling rapid identification of saturated patches before they evolve into deeper ruts [15]. These anomalies are difficult to detect through visual inspection alone, particularly when moisture is distributed heterogeneously across long haul routes. Multispectral reflectance ratios can also distinguish between surface wetness and deeper subsurface moisture intrusion, supporting more nuanced road-maintenance decisions [18]. When combined with high-resolution elevation models derived from drone photogrammetry, moisture-linked deformation zones become clearly visible, allowing early intervention through grading, compaction, or drainage adjustments [23]. This approach significantly reduces the likelihood of truck slowdowns or tire damage caused by unpredictable rut development on busy haul networks.

3.1.2 Slope, Gradient, and Roadwear Mapping

Accurate mapping of haul-road geometry is essential for maintaining safe truck operations and minimizing mechanical stress. Multispectral drones paired with digital terrain modeling generate highly accurate slope and gradient maps that highlight steep sections, misalignments, and cross-grade irregularities that influence truck handling performance [16]. These datasets help operators adjust road designs to maintain optimal grade limits that reduce fuel demand and minimize drivetrain wear. Roadwear detection is further improved by analyzing spectral variations linked to aggregate loosening, surface polishing, and material loss under heavy truck traffic [19]. When

iJETRM
International Journal of Engineering Technology Research & Management
(IJETRM)
https://ijetrm.com/

overlaid with geometric models, spectral indicators provide a multidimensional understanding of road deterioration, guiding targeted maintenance that reduces machine downtime and enhances haul-fleet reliability [21].

3.2 Pit-Wall Stability and Geotechnical Surveillance

Pit-wall stability remains one of the highest-priority safety concerns in open-pit mines, as undetected discontinuities or weakening geological features can lead to catastrophic slope failures. Multispectral drones enable continuous surveillance of pit faces, providing spectral and geometric information that reveals subtle indicators of structural instability [14]. Repeated flights generate time-series datasets that track progressive surface changes, including rock weathering, moisture accumulation, and material degradation patterns [18]. These datasets supplement manual geological mapping by highlighting stability-related attributes that are difficult to observe from the pit floor. Combined with slope-monitoring radar and LiDAR profiles, multispectral data improve the predictive accuracy of geotechnical models, enabling earlier detection of instability pathways and hazardous deformation trends [20]. Spectral signatures associated with oxidation, mineral transformation, and hydration serve as proxies for weakening rock strength, especially in benches subjected to repeated blasting cycles. As operations deepen, multispectral surveillance becomes increasingly valuable for mapping areas of geotechnical concern and prioritizing remediation work such as scaling, bolting, or drainage adjustments [24].

3.2.1 Early Detection of Discontinuities and Weathering

Surface discontinuities including joints, fractures, and bedding planes often present subtle reflectance changes that multispectral sensors capture effectively. Shortwave-infrared responses can highlight clay-rich or altered zones where weathering has reduced rock cohesion [17]. These features, although sometimes nearly invisible in RGB imagery, appear as distinct spectral anomalies that reveal early-stage instability development. By analyzing temporal shifts in reflectance, operators can identify areas where progressive weathering may lead to bench deterioration, toppling potential, or planar failure [22]. This early detection capability enhances geotechnical intervention timing, improving worker safety and reducing production disruptions.

3.2.2 Multispectral Indicators of Slope Failure Risk

Slope failure often manifests through increased moisture retention, oxidation patterns, and surface softening conditions multispectral sensors detect across visible and infrared bands [15]. Near-infrared data reveal water infiltration pathways along weakness planes, while visible-band indices identify color shifts linked to mineral alteration and stress accumulation [19]. These spectral changes, when combined with elevation models, provide a multidimensional risk map that supports proactive slope-stability management. The ability to track these indicators over time enhances early-warning systems and reduces exposure to unforeseen geotechnical hazards [24].

3.3 Blast Performance Observation and Fragmentation Analysis

Multispectral drone imaging provides high-value insights into blast performance by assessing structural conditions before and after detonation. Pre-blast scans identify geological variability, burden irregularities, and moisture zones that affect fragmentation outcomes, improving the precision of blast design [16]. Post-blast surveys then quantify fragmentation quality, enabling operators to evaluate whether blasting objectives were met or require adjustment. Spectral data reveal mineralogical differences and fines distribution patterns that influence diggability and crusher throughput [20]. Time-series multispectral comparisons help correlate pre-blast structural attributes with post-blast breakage responses, creating a robust feedback loop for continuous blast optimization [21]. These capabilities reduce the reliance on manual measurements and increase safety by limiting exposure to unstable muck piles [23]. When integrated with machine-learning classifiers, multispectral datasets offer automated blast-performance grading that significantly improves operational consistency [14].

iJETRM
International Journal of Engineering Technology Research & Management
(IJETRM)
https://ijetrm.com/

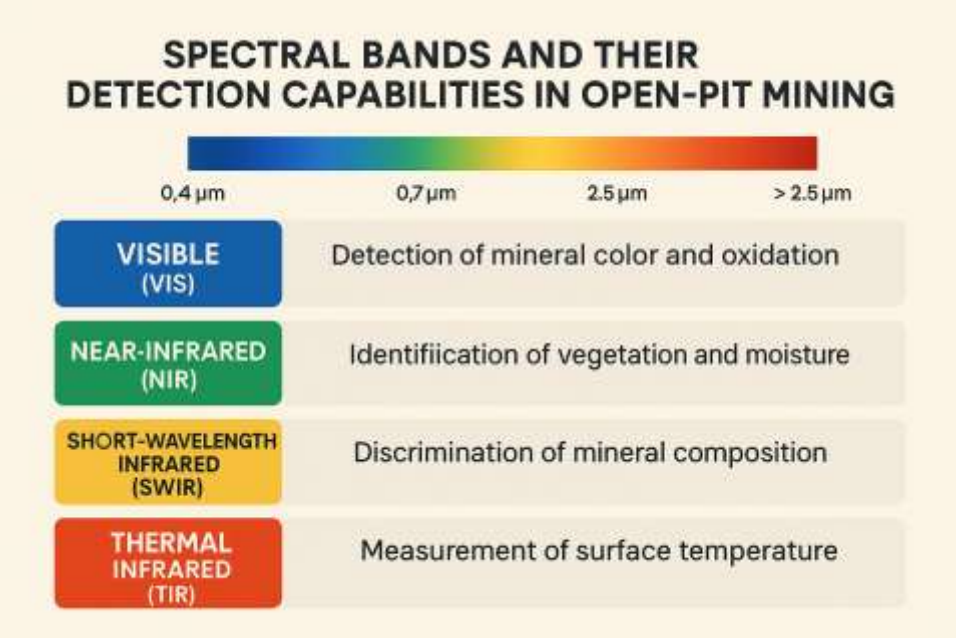

Figure 1. "Spectral Bands and Their Detection Capabilities in Open-Pit Mining."

3.3.1 Pre-Blast Terrain and Burden Assessment

Pre-blast multispectral mapping enhances burden evaluation by identifying lithological contrasts, moisture gradients, and oxidation zones that influence explosive energy distribution [17]. These spectral layers help engineers identify zones requiring charge adjustments or timing modifications. Terrain-adaptive imaging also detects surface heterogeneity that may cause uneven fragmentation or excessive flyrock generation [24]. By integrating spectral data with bench geometry, operators can refine blast patterns to optimize fragmentation outcomes.

3.3.2 Post-Blast Fragmentation Quality Detection

Following detonation, multispectral imagery detects differences in fragment size distribution, fines content, and mineral exposure across the muck pile. Variations in visible and near-infrared reflectance highlight textural contrasts that correlate with fragment size classes [18]. These insights supplement photogrammetric particle-size models, improving blast-performance evaluation and supporting crusher-feed optimization [22]. The integration of spectral and geometric metrics accelerates post-blast assessment while increasing analytical depth.

3.4 Environmental Monitoring and Compliance Applications

Environmental compliance demands continuous monitoring of dust emissions, vegetation health, water movement, and surface degradation. Multispectral drones provide comprehensive coverage of these environmental indicators, enabling mining companies to maintain regulatory compliance and uphold sustainability objectives [20]. By capturing reflectance patterns across sensitive wavelengths, drones support early detection of ecosystem stress, erosion patterns, and chemical contamination [16]. These data help prioritize mitigation strategies and validate rehabilitation progress across disturbed areas [14].

3.4.1 Dust Dispersion and Vegetation Stress Detection

Multispectral imaging identifies dust-affected regions by detecting reductions in vegetation reflectance and changes in canopy health indices [19]. It also maps dust plumes and emission pathways that require operational control measures. This enhances compliance reporting and environmental stewardship [23].

3.4.2 Water Accumulation and Runoff Mapping

Water accumulation zones appear as strong absorptive signatures in near-infrared bands, revealing seepage points, runoff pathways, and potential erosion areas [21]. Mapping these features supports drainage optimization, rehabilitation planning, and environmental risk control [24].

iJETRM
International Journal of Engineering Technology Research & Management
(IJETRM)
https://ijetrm.com/

4. PRODUCTION EFFICIENCY OPTIMIZATION THROUGH SPECTRAL INTELLIGENCE

4.1 Ore–Waste Differentiation and Grade-Control Enhancement

Accurate ore–waste differentiation is one of the most economically significant applications of multispectral drone imaging in open-pit mines. Traditional grade-control methods often rely on limited sampling density, creating substantial uncertainty in material classification and leading to costly misallocation during excavation and haulage operations [22]. Multispectral imaging enhances these workflows by capturing spatially continuous spectral signatures indicative of mineralogical composition, moisture variation, and oxidation states across exposed benches and muck piles. These high-resolution reflectance datasets support refined grade-control models that reduce dilution and increase ore recovery. By integrating near-infrared, shortwave-infrared, and visible reflectance values, operators can generate detailed ore distribution maps that guide shovels and loaders toward more selective extraction strategies [24]. This reduces reliance on manual field mapping and improves the accuracy of cutoff-grade decision-making.

Spectral indices sensitive to clay content, carbonate minerals, and iron oxides assist in distinguishing ore zones from adjacent waste regions with greater confidence than visual inspection alone. As mining progresses, time-series spectral monitoring enables tracking of geological transitions, supporting adaptive grade-control strategies that respond to real-time change in mineralogy [26]. Combined with digital elevation models, spectral layers help quantify ore exposure and thickness variations that influence blasting, digging, and processing efficiency. Automated classification algorithms further enhance ore–waste separation by recognizing subtle spectral patterns that may be overlooked in manual assessments [28]. Ultimately, multispectral imaging strengthens grade-control accuracy, increases resource utilization efficiency, and reduces financial losses associated with misclassification [30].

4.1.1 NIR-Based Material Discrimination

Near-infrared (NIR) wavelengths are highly effective for differentiating ore from waste because many key mining materials exhibit distinct absorption features in this range. NIR imaging detects variations associated with moisture, clay alteration, iron mineralization, and carbonate content, each of which influences ore grade [23]. These reflectance differences remain visible even under non-ideal lighting, providing consistent classification inputs for active mining benches. NIR-based discrimination is particularly valuable when dealing with visually similar lithologies that are difficult to distinguish through color imagery alone [29]. By mapping subtle mineralogical contrasts, NIR sensing supports selective excavation and reduces dilution during loading and hauling activities [27].

4.1.2 Reducing Misclassification in Load-and-Haul Cycles

Misclassification during load-and-haul cycles leads to both revenue loss and downstream processing inefficiencies. Multispectral data help mitigate this challenge by producing real-time material classification layers that loader operators and dispatch systems can use for guided decision-making [25]. Spectral signatures enable rapid identification of ore pockets within mixed zones, ensuring trucks are filled with correctly classified material. This reduces unnecessary blending, minimizes crusher inefficiencies, and prevents high-grade material from being lost to waste dumps [22]. By integrating multispectral classifications with fleet-tracking systems, mines can automate alerts when misloaded trucks enter haul routes, allowing rapid reassignment before material reaches processing facilities [30]. Over time, this improves grade consistency and stabilizes mill feed characteristics.

4.2 Stockpile Management and Material Flow Optimization

Stockpile heterogeneity remains a persistent challenge in mine production planning, affecting blending, processing consistency, and inventory accuracy. Multispectral imaging enhances stockpile monitoring by capturing surface spectral signatures that reveal material composition, weathering intensity, and moisture variation across large volumes [26]. These insights allow operators to maintain tighter control over product quality and reduce variability during blending operations [24]. Spectral layers combined with drone-based elevation models support volumetric estimation, providing a more accurate representation of stockpile growth, depletion, and density distribution than point-based ground surveys [28]. This improves reconciliation workflows and enhances forecasting for feed planning. By tracking material flow from pit to stockpile, multispectral imaging supports real-time optimization of dispatch routes, reducing bottlenecks and preventing oversupply to specific stockpile zones [23]. Overall, the integration of multispectral imagery into stockpile systems reduces re-handling losses, enhances blending accuracy, and ensures more predictable processing performance [29].

iJETRM
International Journal of Engineering Technology Research & Management
(IJETRM)
https://ijetrm.com/

4.2.1 Stockpile Volume Estimation and Moisture Tracking

Stockpile management benefits from precise volume estimation, which drones achieve by integrating digital elevation models with multispectral surface data. Moisture content is detected through reductions in near-infrared reflectance, enabling rapid identification of wet zones that may increase handling difficulty or influence material density [27]. These insights support optimized stacker-reclaimer strategies and help operators better predict stockpile behavior during extended storage periods [30].

4.2.2 Avoiding Cross-Contamination and Re-Handling Losses

Cross-contamination between ore types or waste materials can significantly degrade product quality. Multispectral reflectance maps highlight material boundaries and compositional transitions, enabling more precise loading and reclaiming operations [22]. Operators can use these maps to direct machinery along cleaner extraction pathways, reducing re-handling and improving product consistency [25].

4.3 Maintenance Scheduling and Predictive Insights for Production

Predictive maintenance is essential for sustaining mine productivity, especially in operations with heavy machinery operating under harsh environmental conditions. Multispectral drone imaging provides new avenues for identifying early signs of mechanical wear, road deterioration, and performance degradation across haulage networks [24]. By analyzing reflectance patterns linked to surface texture, aggregate displacement, and moisture penetration, engineers can detect operational stresses that influence both equipment lifespan and production efficiency [26]. Time-series datasets strengthen forecasting models for equipment scheduling, allowing mines to anticipate maintenance before failures occur, reducing downtime and unplanned repair costs [30]. The integration of spectral, geometric, and temporal data offers a powerful toolset for coordinating maintenance with production cycles.

Table 1. Spectral Signatures of Common Mining Materials and Their Operational Implications

Material Type	Key Spectral Characteristics (VIS–NIR–SWIR)	Diagnostic Indicators	Operational Implications in Open-Pit Mining
Iron-Rich Ore (Hematite, Magnetite)	Strong absorption in VIS; high reflectance in NIR; distinct SWIR troughs	Oxidation intensity, grade variability	Enhances ore–waste differentiation, supports grade-control mapping, improves selective loading decisions
Clay-Rich Zones (Kaolinite, Montmorillonite)	Pronounced absorption features in 2100–2300 nm SWIR range	Hydration state, alteration intensity	Identifies geotechnically weak zones, guides slope-stability monitoring, informs blasting adjustments
Carbonate Ores (Limestone, Dolomite)	Sharp absorption near 2330–2340 nm; moderate VIS reflectance	Lithological boundaries, alteration fronts	Improves ore-domain modeling, supports precise burden estimation, reduces dilution during loading
Silica-Rich Waste Rock	Relatively flat VIS–NIR signature; weak SWIR absorption	Degree of weathering, fracture exposure	Aids waste mapping, improves stockpile management, supports haul-route wear prediction
Moist or Saturated Surfaces	Strong reflectance reduction in NIR; spectral darkening across all bands	Moisture pockets, seepage paths	Critical for detecting hazardous ground, optimizing haul-road maintenance, minimizing rut formation
Oxidized / Weathered Surfaces	Red-shifted VIS response; elevated reflectance in red band	Surface weakening, stress accumulation	Supports early detection of slope deterioration and enhances geotechnical surveillance
Explosive Residue & Blast Fines	High reflectance variability; bright VIS response	Fragmentation distribution, fines content	Improves post-blast evaluation, enhances crusher-feed forecasting

iJETRM
International Journal of Engineering Technology Research & Management
(IJETRM)
https://ijetrm.com/

4.3.1 Machine Movement Patterns and Wear Prediction

Machine movement generates characteristic visual patterns along haul roads, benches, and loading zones. Multispectral imaging captures spectral signatures indicative of compaction, material abrasion, and tire-induced polishing [28]. These reflectance trends reveal areas experiencing high mechanical stress, supporting targeted maintenance interventions that reduce component wear. When integrated with fleet-tracking systems, spectral indications of road stress can also be correlated with specific machine behaviors, strengthening predictive wear models [23].

4.3.2 Road Degradation Forecasting Using Spectral Trends

Road degradation manifests through spectral changes associated with aggregate displacement, dust accumulation, and moisture retention [22]. By tracking these trends over time, mines can build predictive models that estimate when specific segments will require grading, compaction, or resurfacing [27]. This reduces emergency maintenance events and supports smoother traffic flow for haulage fleets [25].

4.3.3 Integration with Dispatch and Fleet Management Systems

Integrating multispectral data with dispatch systems allows real-time adaptation of fleet routing, maintenance scheduling, and traffic management [29]. Spectral indicators of deterioration or contamination trigger automated alerts that revise route assignments and reduce machine exposure to damaging conditions [24]. This enhances operational resilience and strengthens coordination between production and maintenance teams [26].

5. DATA PROCESSING, AI INTEGRATION, AND GEOSPATIAL ANALYTICS

5.1 Spectral Data Preprocessing and Noise Reduction Techniques

Effective preprocessing of multispectral drone data is essential to ensure accurate interpretation and robust analytical performance in open-pit mining environments. Raw spectral imagery captured in dynamic operational settings often contains atmospheric interference, illumination variability, sensor drift, and particulate-related distortions that reduce classification and prediction accuracy [28]. Preprocessing resolves these issues by normalizing reflectance values, removing noise, and structuring datasets into analysis-ready formats suitable for machine learning and geospatial modelling. Radiometric calibration aligns image intensities across multiple bands, ensuring that reflectance differences represent true material features rather than sensor anomalies. Atmospheric correction further refines these values by compensating for scattering and absorption effects, especially in dusty or heat-fluctuating mine atmospheres [30]. Preprocessing also includes geometric adjustments to correct lens distortion, terrain-induced perspective variation, and alignment inconsistencies between consecutive flight paths. Together, these steps enable precise downstream modelling, particularly for tasks involving ore–waste differentiation, fragmentation tracking, and pit-wall stability assessment [33]. Without rigorous preprocessing, machine-learning performance deteriorates significantly, undermining digital-twin accuracy and operational decision-support frameworks [32].

5.1.1 Atmospheric Correction and Radiometric Balancing

Atmospheric correction stabilizes spectral data by compensating for scattering, airborne dust, humidity shifts, and solar-angle fluctuations that distort incoming radiance in mining environments [29]. Tools such as empirical line calibration and model-based atmospheric compensation adjust reflectance values to consistent baselines. Radiometric balancing then aligns band intensities across flight sessions, enabling reliable temporal comparisons. These steps are essential for detecting subtle spectral differences associated with mineralogy, moisture, and weathering patterns [34].

5.1.2 Noise Filtering in Harsh Mining Environments

Noise filtering mitigates errors introduced by dust, vibration, shadows, and intermittent sensor occlusions common in active mine sites. Techniques such as median filtering, adaptive smoothing, and band-specific denoising suppress pixel-level disruptions while preserving material signatures relevant to geotechnical and operational analysis [31]. Temporal filtering enhances the stability of time-series datasets, improving machine-learning robustness for predictive mining applications [28].

5.2 Machine Learning Models for Predictive Mining Operations

Machine learning enables the transformation of multispectral datasets into predictive insights that enhance operational efficiency, safety, and mine-planning accuracy. Classification and regression algorithms extract

iJETRM
International Journal of Engineering Technology Research & Management
(IJETRM)
https://ijetrm.com/

patterns across spectral and geometric features, supporting decision-making processes such as ore characterization, slope-risk forecasting, production optimization, and equipment scheduling [35]. These models leverage the spatial continuity of drone imagery to address long-standing data gaps associated with manual sampling and point-based sensors. High-dimensional spectral data provide rich input features for mineral classification, while integrated elevation models strengthen the interpretation of structural and operational context [32]. As mining operations become increasingly automated, machine-learning pipelines facilitate rapid evaluation of changing conditions, triggering alerts for geotechnical risks or deviations in production metrics [30]. Through continuous training and retraining, models evolve with site conditions, improving predictive accuracy over time [34].

5.2.1 Classification Models for Material Identification

Classification algorithms such as random forests, support-vector machines, and convolutional neural networks map ore types, alteration zones, and waste materials by analyzing spectral signatures across multiple wavelength bands [29]. These models outperform manual mapping by capturing subtle spectral differences that correlate with mineralogical or moisture variations. The resulting classification maps guide selective loading, blending, and processing decisions, reducing dilution and improving grade-control performance [33].

5.2.2 Regression Models for Production Forecasting

Regression-based machine-learning models estimate production rates, fragmentation characteristics, and haul-fleet travel times by correlating spectral and spatial variables with operational performance metrics [28]. These models support forecasting of crusher throughput, equipment cycle efficiency, and stockpile evolution. By learning patterns from historical drone datasets, regression engines highlight emerging inefficiencies and provide quantitative predictions that improve forward-looking mine-planning decisions [35].

5.3 Integrating Drone Data into Digital Twin and Mine-Planning Platforms

Integrating multispectral drone imagery into digital-twin ecosystems enhances data continuity, operational transparency, and long-range planning capabilities in open-pit mines. Digital twins replicate geological, structural, and operational realities in real time, enabling predictive simulation and scenario testing informed by drone-derived datasets [32]. Multispectral imagery provides both spectral and spatial detail, improving the fidelity of digital-twin models used for slope-stability analysis, pit sequencing, equipment dispatch optimization, and environmental monitoring [30]. Integration requires standardized geospatial pipelines capable of ingesting drone output, reconstructing 3D surfaces, and aligning spectral layers with mine-planning coordinate systems [34]. Automated update loops ensure that digital twins reflect evolving pit geometries and operational conditions, enabling more responsive decision frameworks and facilitating predictive control across the mine value chain [28].

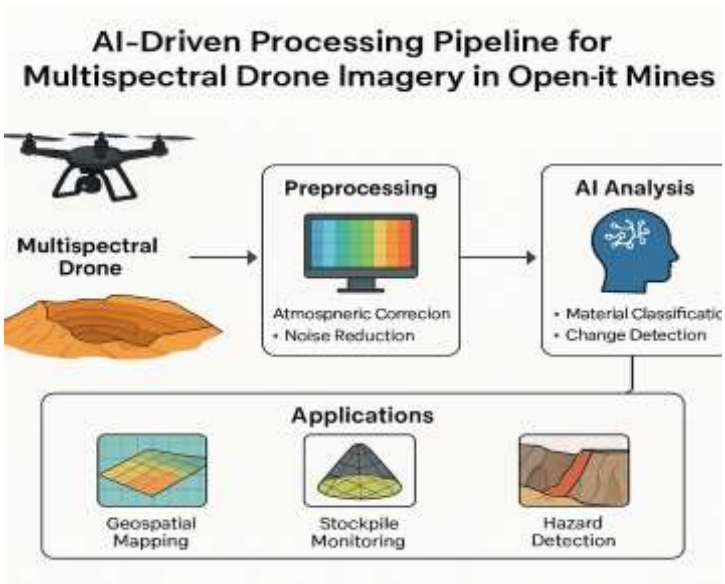

Figure 2. AI-Driven Processing Pipeline for Multispectral Drone Imagery in Open-Pit Mines.

iJETRM
International Journal of Engineering Technology Research & Management
(IJETRM)
https://ijetrm.com/

5.3.1 GIS and 3D Reconstruction Workflows

GIS-based workflows align multispectral datasets with terrain models, block-model boundaries, and geotechnical layers used in mine planning. Photogrammetric reconstruction and LiDAR-assisted modelling generate detailed 3D meshes that integrate seamlessly with multispectral reflectance values [31]. These geospatial products support structural mapping, ore delineation, and operational simulations, strengthening digital-twin accuracy [33].

5.3.2 Real-Time Update Loops for Operational Decision Support

Real-time update loops ensure mining operations reflect the latest field conditions by synchronizing drone inputs with planning dashboards, dispatch systems, and geotechnical alerts [35]. Automated data ingestion enables continuous monitoring of haul roads, pit walls, stockpiles, and blast areas. Spectral and geometric trends are analyzed in near-real time, supporting rapid decisions that enhance safety, predict failure risks, and reduce production delays [28].

6. ECONOMIC, OPERATIONAL, AND SAFETY IMPACTS

6.1 Quantifying Operational Efficiency Gains

Multispectral drone systems generate operational efficiencies across multiple stages of open-pit production by increasing data frequency, enhancing measurement accuracy, and reducing delays associated with manual surveys. High-resolution spectral and geometric datasets enable faster detection of haul-road degradation, moisture accumulation, and pit-wall instability, resulting in more timely maintenance interventions that minimize equipment downtime [32]. Continuous spectral monitoring also enhances the precision of ore–waste differentiation, improving grade-control efficiency and reducing dilution rates that negatively affect downstream processing [36]. Production cycles benefit from improved fragmentation assessment, as drones rapidly capture post-blast conditions and allow supervisors to adjust subsequent blast designs without waiting for manual inspection teams. These insights also accelerate shovel allocation and truck dispatch decisions, shortening cycle times and preventing bottlenecks across the haulage network [34]. Additionally, the integration of drone-derived data into digital-twin platforms enhances predictive modelling accuracy, allowing mines to simulate operational scenarios and evaluate the impacts of design modifications before implementation. This reduces costly trial-and-error approaches traditionally associated with pit expansion and sequencing [38]. Collectively, the efficiency gains generated by multispectral drone workflows strengthen production resilience and increase overall mine productivity.

6.2 Financial Return on Drone-Based Monitoring Investments

Financial returns on multispectral drone investments arise from reduced surveying costs, improved ore recovery, and lower unplanned-maintenance expenditures. Traditional geological mapping and road inspection tasks often require large field teams, repeated manual measurements, and specialized equipment, all of which contribute to recurring operational expenses [35]. Drone-based workflows reduce these costs by providing rapid, repeatable coverage at a fraction of the labor requirements. Enhanced ore–waste classification further increases revenue by preventing high-grade material from being misdirected to waste dumps, improving mill feed quality and stabilizing metal output [33]. Predictive maintenance enabled by spectral indicators reduces emergency repairs, extending the lifespan of haul trucks and loading equipment [37]. When combined, these factors shorten investment payback periods and generate sustained cost savings across production, logistics, and maintenance cycles [32].

6.3 Safety Enhancements and Reduction of Worker Exposure

Multispectral drones significantly strengthen mine safety by reducing worker exposure to hazardous operational zones. High walls, unstable benches, active blast areas, and saturated haul-road segments present substantial risk during manual inspections, yet drones can assess these areas remotely with no direct human presence required [38]. Spectral detection of moisture, oxidation, and early-stage rock deterioration provides advanced warning of geotechnical hazards that may not be visible from the ground [34]. Drone-enabled post-blast assessments further minimize the need for geologists and surveyors to enter freshly blasted or still-unstable muck piles [36]. This reduces the likelihood of accidents related to rockfalls, equipment interactions, and surface collapse. Enhanced visibility into unsafe conditions allows supervisors to implement timely safety interventions, improving compliance with regulatory requirements and strengthening the mine's overall risk-management culture [33].

iJETRM
International Journal of Engineering Technology Research & Management
(IJETRM)
https://ijetrm.com/

7. IMPLEMENTATION BARRIERS AND FUTURE TECHNOLOGICAL OPPORTUNITIES

7.1 Barriers to Adoption: Technical, Organizational, and Regulatory

Despite rapid advancements, several challenges continue to limit widespread adoption of multispectral drone technologies in open-pit mining. Technically, drone operations must contend with dust, turbulence, electromagnetic interference, and steep pit geometries that complicate both flight stability and spectral data quality [32]. Sensor calibration can be difficult to maintain under fluctuating temperatures and illumination conditions, while data transmission bandwidth remains a constraint for high-density spectral missions. Organizational barriers also slow adoption, as mining companies must adapt internal workflows, train personnel, and integrate new sensing modalities into legacy systems that were not designed for continuous spectral monitoring [35]. Resistance may arise due to perceived disruptions to established grade-control, geotechnical, or dispatch routines. Regulatory limitations create additional hurdles, with flight-approval processes, beyond-visual-line-of-sight restrictions, and evolving air-safety mandates varying by jurisdiction [38]. Mines must also address cybersecurity risks associated with transmitting high-value operational data. Collectively, these barriers underscore the need for standardized operating protocols, robust sensor and drone certification frameworks, and organizational change strategies that encourage confident adoption of spectral drone workflows [40].

7.2 Advances in Autonomous Drone Swarming and Edge Processing

Autonomous drone swarms represent a major technological step forward, enabling multi-platform spectral coverage of large pits within minutes rather than hours. Swarming algorithms coordinate simultaneous flight paths, dynamic obstacle avoidance, and distributed sensing patterns that increase spatial resolution while reducing mission duration [36]. When combined with onboard edge-processing units, drones can analyze multispectral data in real time, generating immediate hazard alerts, classification layers, and geotechnical insights without relying heavily on remote servers [34]. Edge processing also improves operational resilience by reducing data-transfer loads and enabling drones to function in areas with limited connectivity, such as deep or stepped pit geometries [32]. As models become more efficient, autonomous swarms may support continuous monitoring loops that update mine-planning systems in near real time [39].

7.3 Opportunities for Fully Automated, Spectrally Intelligent Mines

Future open-pit mines have the potential to become fully automated, “spectrally intelligent” environments where multispectral drones function as core components of autonomous operational ecosystems. Continuous spectral mapping can feed directly into digital-twin engines, enabling real-time simulations of ore distribution, slope stability, stockpile evolution, and equipment movement [37]. Automated decision frameworks could reroute haul trucks, trigger predictive-maintenance alerts, or adjust blast parameters based on live spectral indicators [33]. Integration with robotic drilling, autonomous shovels, and AI-enabled fleet management platforms would create a tightly coordinated mine where operational decisions are driven by continuous spectral intelligence rather than periodic manual observations [40]. Such systems promise unprecedented precision in grade control, production optimization, and safety assurance, accelerating the industry’s evolution toward high-efficiency, low-exposure mining workflows [38].

8. CONCLUSION

Multispectral drone imaging represents a fundamental turning point in how open-pit mines are monitored, managed, and optimized. By capturing rich spectral signatures that reveal mineralogical variation, moisture conditions, structural weakness, and environmental change, these systems provide an unprecedented level of visibility into dynamic mining environments. Their ability to deliver continuous, high-resolution data across vast and hazardous areas transforms decision-making from reactive assessments to proactive, information-driven strategies. This shift enables more precise grade control, improved blasting outcomes, optimized haul-road performance, and more reliable stockpile management, directly contributing to higher productivity and reduced operational uncertainty.

Equally transformative is the technology’s impact on safety. Multispectral drones remove workers from high-risk zones by autonomously inspecting pit walls, blast areas, saturated ground, and unstable benches. When integrated into digital-twin ecosystems, these spectral datasets allow real-time simulations and predictive insights that support faster, more informed responses to geotechnical hazards and operational disruptions.

As mining operations continue to evolve toward automation and AI-enabled management, multispectral drone imaging will become a core component of digitally integrated mines. Its increasing precision, adaptability, and

iJETRM
International Journal of Engineering Technology Research & Management
(IJETRM)
https://ijetrm.com/

compatibility with autonomous systems position it as a foundational technology for building safer, smarter, and more efficient open-pit mining operations in the decades ahead.

REFERENCE

1) Bamford T, Medinac F, Esmaeili K. Continuous monitoring and improvement of the blasting process in open pit mines using unmanned aerial vehicle techniques. Remote Sensing. 2020 Aug 29;12(17):2801.
2) Salam A. Internet of things for sustainable mining. InInternet of Things for Sustainable Community Development: Wireless Communications, Sensing, and Systems 2019 Dec 29 (pp. 243-271). Cham: Springer International Publishing.
3) National Research Council, Committee on Earth Resources, Board on Earth Sciences, National Materials Advisory Board, Committee on Technologies for the Mining Industries. Evolutionary and revolutionary technologies for mining. National Academies Press; 2002 Mar 14.
4) Roper WE, Dutta S. Remote sensing and GIS applications for pipeline security assessment. In2005 ESRI User Conference Proceedings 2005 Nov (Vol. 15).
5) Kruse FA, Bedell RL, Taranik JV, Peppin WA, Weatherbee O, Calvin WM. Mapping alteration minerals at prospect, outcrop and drill core scales using imaging spectrometry. International Journal of Remote Sensing. 2012 Mar 20;33(6):1780-98.
6) Moomen AW, Bertolotto M, Lacroix P, Jensen D. Inadequate adaptation of geospatial information for sustainable mining towards agenda 2030 sustainable development goals. Journal of Cleaner Production. 2019 Nov 20;238:117954.
7) Tang M. Advances in Heap Leach Pad Surface Moisture Mapping using Unmanned Aerial Vehicle Technology and Aerial Remote Sensing Imagery. University of Toronto (Canada); 2020.
8) Barrett BJ. Field Validation of an Advanced Autonomous Method of Exterior Dam Inspection Using Unmanned Aerial Vehicles. Brigham Young University; 2018.
9) Green J. Requirements elicitation techniques for the development of an underground remote piloted aerial system. University of Johannesburg (South Africa); 2017.
10) Rutkowski J, Niemeyer I. Remote sensing data processing and analysis techniques for nuclear non-proliferation. InNuclear Non-proliferation and Arms Control Verification: Innovative Systems Concepts 2020 Mar 13 (pp. 339-350). Cham: Springer International Publishing.
11) Thumser P, Kuzovlev VV, Zhenikov KY, Zhenikov YN, Boschi M, Boschi P, Schletterer M. Using structure from motion (SfM) technique for the characterisation of riverine systems-Case study in The Headwaters of the Volga River. Geography, Environment, Sustainability. 2017;10(3):31-43.
12) Bedell RL, Rivard B, Browning D, Coolbaugh M. Thermal Infrared Sensing for Exploration and Mining–an update on relevant systems for remote acquisition to drill core scanning. InProceedings of Exploration 2017 (Vol. 17, pp. 881-897).
13) Wang L, Yan J, Ma Y. Cloud computing in remote sensing. Chapman and Hall/CRC; 2019 Jul 11.
14) Hunt GR. Spectral signatures of particulate minerals in the visible and near infrared. Geophysics. 1977 Apr;42(3):501-13.
15) Prasanth NN, editor. Cloud IoT systems for smart agricultural engineering/Saravanan Krishnan, J Bruce. Irrigation and Drainage. 2017;62(3):255-61.
16) Bailey JE, Williams J. The Legacy of Google Earth in Remote Sensing. InRemote Sensing Handbook, Volume I 2016 (pp. 441-462). CRC Press.
17) Awange J, Kiema J. Light detection and ranging (LiDAR). InEnvironmental Geoinformatics: Extreme Hydro-Climatic and Food Security Challenges: Exploiting the Big Data 2018 Dec 8 (pp. 291-306). Cham: Springer International Publishing.
18) Team HM. HyspIRI final report. Jet Propulsion Laboratory, California Institute of Technology: Pasadena, CA, USA. 2018 Sep.
19) Koepsell RW, Cramer GL, Ambrosich KL, Colarco LI. Passive Remote Sensing of Meteorological Parameters. 1994 Dec 28.
20) Zhong L, Liu X, Yang P, Lin R. Explore the application of high-resolution nighttime light remote sensing images in nighttime marine ship detection: A case study of LJ1-01 data. Open Geosciences. 2020 Oct 31;12(1):1169-84.
21) Tarolli P, Cao W, Sofia G, Evans D, Ellis EC. From features to fingerprints: A general diagnostic framework for anthropogenic geomorphology. Progress in Physical Geography: Earth and Environment. 2019 Feb;43(1):95-128.

iJETRM
International Journal of Engineering Technology Research & Management
(IJETRM)
https://ijetrm.com/

22) Sreedhar M, Narender B, Muralikrishnan S. Line of sight analysis for urban mobile applications: a photogrammetric approach. Applied GIS. 2017 Nov 1;13(2).
23) Kalabokidis K, Ager A, Finney M, Athanasis N, Palaiologou P, Vasilakos C. AEGIS-Wildfire Prevention and Management Information System. InBook of Abstracts of the International Conference on Fire Behaviour and Risk 2015 Oct (pp. 26-29).
24) Mazur CJ, Sendeckyj GP, Stevens DM. Air force smart structures/skins program overview. InFiber Optic Smart Structures and Skins 1989 Jan 16 (Vol. 986, pp. 19-31). SPIE.
25) Liu H, Yu Q, Ding W, Ni D, Wang H, Shannon S. Feasibility study for automatic calibration of transportation simulation models. InProceedings of the 44th Annual Simulation Symposium 2011 Apr 3 (pp. 87-94).
26) Rumbidzai Derera. HOW FORENSIC ACCOUNTING TECHNIQUES CAN DETECT EARNINGS MANIPULATION TO PREVENT MISPRICED CREDIT DEFAULT SWAPS AND BOND UNDERWRITING FAILURES. International Journal of Engineering Technology Research & Management (IJETRM). 2017Dec21;01(12):112–27.
27) Karimi HA, editor. Telegeoinformatics: Location-based computing and services. CRC press; 2004 Mar 15.
28) Eze Dan-Ekeh. DEVELOPING ENTERPRISE-SCALE MARKET EXPANSION STRATEGIES COMBINING TECHNICAL PROBLEM-SOLVING AND EXECUTIVE-LEVEL NEGOTIATIONS TO SECURE TRANSFORMATIVE INTERNATIONAL ENERGY PARTNERSHIPS. International Journal Of Engineering Technology Research & Management (IJETRM). 2018Dec21;02(12):165–77.
29) Khalid N. *An Application of Remote Sensing to a Copper Porphyry Site in Central Peru* (Master's thesis, The University of Western Ontario (Canada)).
30) Kalabokidis K, Ager A, Finney M, Athanasis N, Palaiologou P, Vasilakos C. AEGIS: a wildfire prevention and management information system. Natural Hazards and Earth System Sciences. 2016 Mar 4;16(3):643-61.
31) Derera R. Machine learning-driven credit risk models versus traditional ratio analysis in predicting covenant breaches across private loan portfolios. *International Journal of Computer Applications Technology and Research*. 2016;5(12):808-820. doi:10.7753/IJCATR0512.1010.
32) Dold J, Groopman J. The future of geospatial intelligence. Geo-spatial information science. 2017 Apr 3;20(2):151-62.
33) Yeomans CM. Enhancing the Geological Understanding of Southwest England Using Machine Learning Algorithms. University of Exeter (United Kingdom); 2018.
34) Terblans YM. *How sustainable is road transport in Gauteng, South Africa? An analysis of the R59 from the perspective of traffic volumes and vehicle loading* (Master's thesis, University of Johannesburg (South Africa)).
35) Behera S, Pattnaik J, Mohanty DD. Mineral Exploration: Integrating Remote Sensing, GIS, AI, and Seismic Methods. InRemote Sensing for Geophysicists (pp. 460-471). CRC Press.
36) Yan Y, Ran M, Sandberg U, Zhou X, Xiao S. Spectral techniques applied to evaluate pavement friction and surface texture. Coatings. 2020 Apr 24;10(4):424.
37) Gadja JW, VanGeem MG. A comparison of six environmental impacts of Portland cement concrete and asphalt cement concrete pavements. PCA R&D Serial. 2001;2068.
38) Atanda ED. EXAMINING HOW ILLIQUIDITY PREMIUM IN PRIVATE CREDIT COMPENSATES ABSENCE OF MARK-TO-MARKET OPPORTUNITIES UNDER NEUTRAL INTEREST RATE ENVIRONMENTS. International Journal Of Engineering Technology Research & Management (IJETRM). 2018Dec21.;2(12):151-64.
39) Wang D, Liu P, Wang H, Ueckermann A, Oeser M. Modeling and testing of road surface aggregate wearing behaviour. Construction and Building Materials. 2017 Jan 30;131:129-37.
40) Moaveni M. Advanced image analysis and techniques for degradation characterization of aggregates. University of Illinois at Urbana-Champaign; 2015.