A review of remote-sensing unmanned aerial vehicles in the mining industry

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Synopsis

The increased adoption of unmanned aerial vehicles (UAVs) may improve the productivity and cost-effectiveness of remote sensing in the mining industry. This review's objective is to enable stakeholders to identify possible application adoption, improvement, and innovation opportunities. The review merges a building block strategy and practical screening criteria to identify possible avenues of research to answer the review questions. After the screening process, 72 documents were included in the review. Papers were classified into four categories: exploration, development, exploitation, and reclamation. Fifteen applications were identified, the majority of which were in the exploration phase. The most often researched applications were topographic surveys, reclamation monitoring, and slope management. From the two UAV types identified, multi-rotor vehicles were the most favoured for all applications. From the eight remote sensing techniques identified, photogrammetry was the one most often used. Other techniques were limited because of complexity, cost, or the incompatibility of sensors and UAVs. The review was limited to published papers in academic journals. Future studies could aim to include empirical data on the latest UAV applications used in the mining industry.

Keywords

UAV, remote sensing, mining industry, photogrammetry, monitoring, detection.

Introduction and background

Remote sensing is the science of capturing data with a device that is not in physical contact with the data source. The output is used to create a digital representation of the object. Unmanned aerial vehicles (UAVs) have become favoured instruments for remote sensing applications (Muchiri and Kimathi, 2016). UAVs are capable of sustaining flight without onboard human involvement (Bento, 2008), and are remotely controlled either manually or by a computerized piloting program. The recent enhancement in UAVs, along with remote sensing technologies, have ensured an ever-expanding field of application in industries such as agriculture, forestry, surveying, construction, entertainment, and mining.

Although sensor-equipped UAVs are relatively new to the mining industry, their application has snowballed in terms of scale, speed, and service scope (Ren *et al*., 2019). For example, Szentpeteri (2016) investigated the use of UAVs for geological modelling and surface pit mapping. Jones *et al*. (2019) identified advances in applying autonomous UAVs in underground mines. Park and Choi (2020) focused on the applications of UAVs in mineral exploration, exploitation, and reclamation.

This article reviews the status of published academic research in the field and aims to answer the following two questions:

1. Which applications of remote-sensing UAV technology are used in the four phases (exploration, development, exploitation, and reclamation) of mining?
2. Which types of UAV and remote sensing methods are typically used in these applications?

The results may enable researchers to identify gaps in the published research or potential collaborators. In addition, other stakeholders may use re findings to identify possible opportunities for application adoption, improvement, and innovation.

Review method

Search strategy and screening process

A building-blocks search strategy was used to perform a systematic literature review. The three search terms used were 'remote sensing', 'UAV', and 'mining'. The Boolean operator 'AND' was used to include only papers that were relevant for all the terms. The search results excluded 'data mining', and included the following journal paper provisos:

1. South African (SA) Department of Higher Education and Training (DHET) approved journal list
2. Published between 2010 and 2020
3. Indexed in the Scopus or Web of Science databases
4. Written in English
5. Available electronically
6. Relevant to the research questions.

The Scopus database was selected because it is one of the most extensive and most popular databases in the engineering disciplines, and provides the largest number of abstracts and peer-reviewed publications(Roux, van der Lingen, and Botha, 2019); while Web of Science is known as a database in leading scholarly research in the sciences worldwide. Following this screening process, only 72 papers remained from the initial sample.

Data extraction

In the data extraction process, the relevant information is taken from the individual research and stored in a single format (Boland, Cherry, and Dickson, 2017). A total of 72 articles and reviews were eligible for inclusion in the review. Microsoft Excel and ATLAS.ti software were used to extract meaningful data from the screened papers. Full-text academic material was imported into ATLAS.ti and subsequently coded.

Methods of synthesis and analysis

This review was a qualitative study, leaning towards an integrative approach. According to Boland, Cherry, and Dickson (2017), an integrative approach aggregates the primary research data. Therefore it summarizes already defined themes that are used in the industries in such a way that the review questions posed by the specific systematic literature review are answered. The developed codes included were 'mining applications', 'UAV type', 'sensor type', 'remote sensing technique', and 'remote sensing outputs'. The coded documents were grouped according to their applicability to the four phases in mining.

Limitations

The research considered only publications related to mining applications in DHET-approved journals indexed in the Scopus or Web of Science databases. It didn't consider unpublished developments in the industry, research that is kept confidential, or developments for which there are approved or pending patent applications. It also didn't consider developments in related fields that might potentially be implemented in the mining industry. However, the results are relevant to researchers and stakeholders in the mining field since they can use them to identify potential applications, gaps in academic publications, and collaborators.

Year of publication

After the screening process, only articles published from 2015 to 2020 remained in the sample, even though the original search parameters were from 2010 to 2020. The earlier publications focused on how UAV technology can supplement manual methods, but the more recent publications emphasized stand-alone utilizations of UAVs.

Publication sources, research type, and country of origin

The journals with the most publications were Remote Sensing with nine publications, Sensors with eight, Environmental Earth Sciences with five, and Acta Montanistica Slovaca with three. China (21%) was the top contributor, with Australia (8%) and Italy (8%) following. South Africa published only one article on the review topic.

Papers per mining phase and application type

Figure 1 illustrates the number of papers per mining phase and application type. Of the 72 documents reviewed, the majority

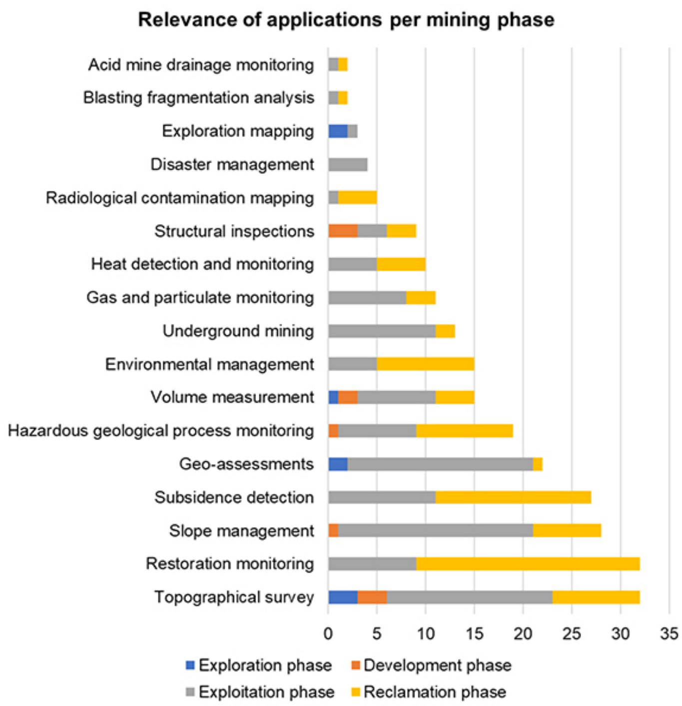

Figure 1—Applications per mining phase

concerned the exploitation (51) and reclamation phases (41). Several papers included more than one phase. Topographic surveying and restoration monitoring were the applications most frequently observed. The various applications and research findings per phase are discussed in the sections that follow.

Results

Exploration phase

Four applications – exploration mapping, topographic survey, geo-assessment, and volume measurement – are relevant to this phase, as indicated in Figure 1. Exploration mapping examines the relationship between mineral deposit characteristics and surface geology. Remote sensing technologies used for this include magnetic, hyperspectral, and photogrammetric.

Magnetic imaging uses fluxgate magnetometers to detect variations in the Earth' s magnetic field due to ferromagnetic minerals' magnetism (Heincke *et al*., 2019). Hyperspectral imaging is used for a broader range of minerals, since every compound displays a unique spectral signature based on the wavelengths of electromagnetic radiation absorbed, emitted, or reflected (Kirsch *et al*., 2018). An example of a hyperspectral sensor is the visible to near-infrared (VNIR) camera, Senop Rikola, which was used by both Heincke *et al.* (2019) and Kirsch *et al.* (2018) in their studies of exploration mapping. Photogrammetry uses multiple 2D images of objects and reconstructs them into a 3D point cloud using triangulation. The models thus created can be grouped as digital elevation models (DEM), digital surface (DSM) models, digital terrain (DTM) models, and orthophotographs or 3D models. Photogrammetry can also be used for RGB (red-green-blue) analysis, which mimics human vision by differentiating objects based on their colour.

Kirsch *et al.* (2018) integrated terrestrial and UAV exploration surveys by using hyperspectral imaging and photogrammetry. They demonstrated multiple benefits from this integration, such as spectral range, spatial coverage, flexibility, and appropriate validation. The study concluded that remote-sensing-enabled UAVs improve time-efficiency and geological interpretation, and reduce costs. Heincke *et al.* (2019) used magnetic, hyperspectral, and photogrammetry data-enabled UAVs to produce an integrated mineralogical property map under the EU-funded MULSEDRO project.

Fixed-wing or multi-rotor UAVs can be used to transport the sensors. For exploration mapping, both multi-rotor and fixed-wing UAVs are used. For surveys that require low-elevation and high-resolution data, the multi-rotor UAV is preferred. For coverage of large areas that require longer endurance, the fixed-wing UAV is preferred. Heincke *et al.* (2019) indicated that fixed-wing UAVs are preferable for magnetic mapping, as the multi-rotor UAV motors cause electromagnetic noise that distorts the magnetic sensor readings. Advances in exploration mapping will be dependent on the development of smaller and more lightweight sensors with an extended wavelength range for hyperspectral imaging, and higher resolution for digital cameras (Kirsch *et al*., 2018). The development and implementation of hydrogen fuel-cell (de Wagter *et al*., 2020) and hybrid energy systems may also increase flight endurance (Özbek *et al.* 2020).

Development phase

The development phase typically includes construction activities such as buildings, infrastructure, and plant used for ore processing, and mineshafts. Within this phase, four applications were identified: slope management, structural inspections, topographic inspections, and volume measurement (see Figure 1).

Surface deformation analysis (SDA) is a method used for structural inspections, employing dense geo-referenced point clouds. The latest point cloud is compared with earlier ones to identify any possible displacement. SDA inspections are traditionally completed by using 3D laser scanners, but remote-sensing UAVs comply with the technical requirements for SDA inspections (Pinto *et al*., 2020). Photogrammetry is typically used for SDA on UAVs. Structure from motion (SfM) analysis is used with ground-control points to ensure that images are correctly orientated and geo-referenced (Pinto *et al*., 2020). Pinto *et al.* (2020) considered the inspection of both a rocky slope and a dam wall to test UAV photogrammetry's applicability to SDA. The inspections were carried out with a multi-rotor UAV equipped with a digital camera and using an aerial robotics cognitive architecture (ARCog) enabling semi-autonomous flight. Decisions were based on the visual data gathered, as well as pre-programmed rules developed and provided by experts under well-known conditions. The project proved that semi-autonomous flights are possible for visual and 3D inspections. Several advantages were highlighted, such as the ability to access difficult areas and to carry out safe and fast inspections. Future work will look into implementing ARCog on multiple UAVs, and developing several machine-learning opportunities such as new behaviour training during missions and improving decision-making processes (Pinto *et al*., 2020).

Exploitation phase

The exploitation phase is the core of the mining process. This is where the minerals are extracted from the earth and processed into saleable products. The majority of remote-sensing UAV applications are prominent in this phase. Figure 2 is a Sankey diagram for the exploitation phase, showing the applications involved in it. The thickness of the connection line (between phase and application) illustrates the ratio of papers related to both aspects.

The findings per application type in the exploitation phases are summarized in Table I.

Reclamation phase

This phase focuses on environmental management and restoration monitoring. Applications include acid mine drainage, radiological contamination mapping, restoration monitoring, and subsidence detection.

Acid mine drainage monitoring

Acid mine drainage (AMD) originates from mining operations that produce acidic water and mine waste characterized by low pH values. Its environmental impact has led to a demand that AMD be monitored to enable mitigating strategies. Jackisch *et al.* (2018) investigated hyperspectral imaging integrated with photogrammetry for AMD mapping. Hyperspectral UAV sensing was used to gather the AMD mineral composition data. Common AMD minerals are jarosite, schwertmannite, goethite, and haematite (Jackisch *et al*., 2018). These minerals form the basis for mapping AMD areas. A Rikola hyperspectral camera was used on a multi-rotor UAV, which can capture images while hovering. A fixed-wing UAV was used to produce orthophotos and DEM with photogrammetry. The fixed-wing was chosen because it

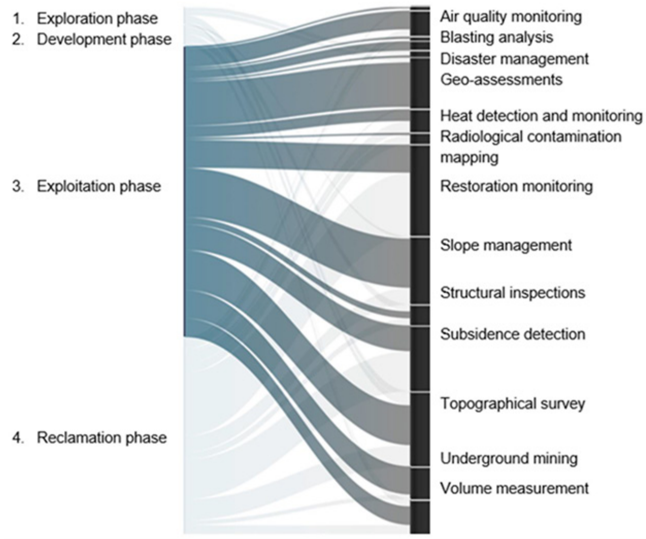

Figure 2—Exploitation stage applications

is able to cover a large area owing to its long flight endurance. Both UAVs flew autonomous flights after flight pre-planning. The study used data from surface sampling, such as chemical analysis by spectrometry and pH measurement, for verification and confirmed the feasibility of monitoring AMD with hyperspectral-enabled UAVs.

Radiological contamination mapping

Uranium mining produces waste and tailing storage facilities with high concentrations of radionuclides (Borbinha *et al*., 2020). These areas pose a high risk to humans, fauna, and flora. Radiological mapping aims to locate, identify, and quantify radiation sources (Borbinha *et al*., 2020). Martin *et al.* (2015) used a UAV at low altitude to perform radiological mapping of a disused mining site. The multi-rotor UAV was equipped with a GPS module, a gamma-ray spectrometer sensor, and a laser rangefinder. The gamma-ray spectrometer was a cadmium zinc telluride (CZT) detector. This recorded a spectrum of radiation energy with a time, location, and elevation stamp. The radiation map depicted the radiological intensity of the area by means of a scaled colour overlay. The survey produced metre-scale-accurate radiation measurements within a much shorter time-frame than traditional methods. The data also allowed isotopic fingerprinting of the region to determine the nature of the contamination. Borbinha *et al.* (2020) employed multi-rotor UAVs with GMCs (Geiger-Muller counters) and CZT gamma-ray spectrometers. A LiDAR UAV was used to develop a 3D model of the studied area. The GMC UAV drone was deployed over the entire area to detect hotspots, after which it hovered close to the ground to gather accurate readings. This allowed the CZT UAV to be deployed in specific hotspot areas to acquire the source spectra (Borbinha *et al*., 2020). This flight strategy provided radiological contamination maps that could be used for monitoring and control.

Restoration monitoring

Mining operations can cause geomorphic changes owing to their anthropogenic nature (Xiang *et al*., 2018). Mining rehabilitation and restoration monitoring track progress to determine whether restoration activities are effective. UAVs can capture data on the surface conditions and ecology, and track the process of restoration (Said *et al*., 2020).

Haas *et al*. (2016) used photogrammetry to evaluate the impact of geomorphic processes (weathering and erosion) on recultivated mining slopes. Yucel and Turan (2016) used it to determine the anthropogenic and meteorological effects on mine lakes in Turkey. Both studies confirmed that photogrammetry is a useful visualization tool, that can rapidly and accurately detect chang. Xiang *et al.* (2018) used photogrammetry, DoD, and SLLAC to determine the geomorphic changes during and after mining. DoD was used to calculate the volumetric changes, while SLLAC was used to determine the extent of the mining and to visualize changes to the mine slopes. Gong *et al.* (2019) used a similar method to assess the effect of erosion on a mine dump site during a freeze–thaw cycle. Satellite images were compared with UAV photogrammetry to quantify the impact of mining on a forest area. Incekara *et al.* (2017) concluded that UAVs are a more appropriate option than satellite images for monitoring the effects of mining in forested areas. UAV data has higher spatial, spectral, radiometric, and temporal resolutions, with fewer cost and time implications.

Kun (2019) used UAV photogrammetry to develop vegetation index maps of a rehabilitated mine dump site. The maps were used to determine the plant species' adaptation, condition, and survival percentage. The RGB values of the surveyed area were used and characterized according to the triangular greenness index (TGI) and the visible atmospheric resistant index (VARI). Padró *et al.* (2019) used a multi-rotor UAV equipped with a multispectral sensor to develop DSM, DEM, DTM, vegetation indices, and orthophoto maps showing land cover classifications. This provided to be a fast, high-resolution, and low-cost alternative to traditional restoration monitoring methods. Carabassa *et al.* (2020) also looked into the use of multispectral sensor UAVs and RGB-enabled digital cameras to determine the land cover classifications of mining areas. Isokangas *et al.* (2019) evaluated the use of thermal infrared (TIR)- and colour infrared (CIR)-enabled UAVs as a monitoring system for peatland used to purify mine process water. The output consisted of TIR images and blue- normalized difference vegetation index (BNDVI) images. The TIR images indicated cold anomalies, which outlined areas of groundwater seepage, and the BNDVI indicated whether or not vegetation was stressed because of excess water. The method was found to be successful in monitoring treatment peatlands.

Table I

Summary of exploitation phase findings

Application	Findings	Reference
Blasting analysis	Fragmentation analysis using photogrammetry with multi-rotor UAVs is preferred.	Said *et al.*, 2020
Disaster management	UAVs can create 3D models of post-seismic building collapses, which improves rescue planning and response time.	Yao, Qin and Chen, 2019
	A multi-rotor UAV was employed to carry a high-definition video camera and Drager XAM 5000 multi-gas detector. The sensor was able to monitor simultaneously five gases that can lead to explosion-prone conditions. Future developments may include flight-enhancement surveillance and measurement by integrating thermal infrared sensors to detect objects in vision-impaired situations, and using LiDAR to avoid collisions and produce 3D images.	Irimia *et al.*, 2019
Air quality monitoring	Mining operations can produce noxious or toxic gases and particulates that can negatively affect the environment, surrounding communities, and mine employees.	Said *et al.*, 2020
	UAVs can be used to characterize blasting plumes (gas and particulate emissions) in near real-time. Fixed-wing and multi-rotor UAVs with autonomous flight path planning were used.	Alvarado *et al.*, 2015
	Underground coal fires waste a valuable energy source, and emit various gases such as carbon dioxide, carbon monoxide, sulphur, and methane. Various sensors, including infrared, catalytic, metal oxide, and electrochemical sensors, can be used in combination to detect gases.	Dunnington and Nakagawa, 2017
Geo-assessments	UAVs have the advantage of being able to reach areas that traditional remote-sensing methods cannot reach. Assessments of these areas are important for stability analysis and planning. UAV photogrammetry is the dominant remote-sensing technique used for geo-assessment in surface mining.	Said *et al.*, 2020
	3D, DSM, orthophotographs, DTM, and DEM can be used to develop models for geological measurements, such as angle of inclination and other structural parameters.	Blistan *et al.*, 2016 Salvini *et al.*, 2018 Katuruza and Birch, 2019
	Photogrammetry with terrestrial laser scanning and distributed optical fibre sensors (DOFS) can monitor strain and temperature to confirm the stability of quarry slopes and subsequently update geological models.	Lanciano & Salvini, 2020
	The evolution of geo-assessments can be automated by employing machine-learning techniques to classify lithologies for geological mapping.	Beretta *et al.*, 2018 Beretta *et al.*, 2019a Beretta *et al.*, 2019b
Heat detection and monitoring	Underground coal fires can lead to surface subsidence and surface fissures, causing geological disasters. Detecting and monitoring fires is crucial to helping with suppressing fires and predicting changes. A terrestrial infrared thermal imager can provide a surface temperature field model.	Wang *et al.*, 2015
	Infrared thermal-enabled UAVs can be used to detect coal fires and overheating of equipment and facilities.	Lee and Choi, 2016 Ren *et al.*, 2019 He *et al.*, 2020 Said *et al.*, 2020
Slope management	Slope stability is vital for safe and continuous production in opencast mines.	Ren *et al.*, 2019
	Slope monitoring allows slope failure to be predicted, ensuring that it can be successfully managed.	Said *et al.*, 2020
	A framework for integrating UAV-based photogrammetry and total laser scanning (TLS) can provide 3D models of mining slopes to map and monitor their condition.	Tong *et al.*, 2015
	TLS can be used for kinematic analysis to identify the most probable failure mechanism of slopes.	Francioni *et al.*, 2015
	Photogrammetry with traditional surveying techniques can be used for geodata-based analysis to identify unstable slope areas.	Leo Stalin and Gnanaprakasam, 2020
	A global navigation satellite system (GNSS) can be used to identify displacement locations. UAV-photogrammetry can then determine the possible causes and the size of displacements. Methods such as slope local length and autocorrelation (SLLAC) and surface peak curvature (SPC) are used on DSMs and retrieved using photogrammetry, allowing a detailed view of mining extent and its terraces. This ability to detect terraces enables SLLAC to monitor their stability.	Gül, Hastaoğlu and Poyraz, 2020 Xiang *et al.*, 2018
	UAV-photogrammetry can be used to appraise slope failures in iron ore mines. ShapeMetrix can generate 3D models from images obtained, and provide a direct analysis of geometric entities such as geological structures, bedding planes, and joints.	Bar *et al.*, 2020
Topographical survey	Compared with traditional surveying techniques such as laser scanning, UAV photogrammetry provides faster, more cost-effective, and higher spatial data outputs.	Kršák *et al.*, 2016 Blistan *et al.*, 2019 Beretta *et al.*, 2018
	Spectral imaging and photogrammetry can be used to develop land cover classification maps for rehabilitation planning	Carabassa *et al.*, 2020

Table I (continued)

Application	Findings	Reference
Volume measurement	Volume measurements are used in mine planning to determine the extraction rate and estimate stripping ratios. Photogrammetry is the preferred technique for this.)	Esposito *et al.*, 2017 Shahbazi *et al.*, 2015
	Volume measurement requires a 'before' and an 'after' model of the mining area to determine the amount of excavated material by calculating the difference between the two models.	Esposito *et al.*, 2017
	Fixed-wing and multi-rotor UAVs are prevalent in this application. Since two different models are compared for volume measurement, geo-referencing of the images is critical. Indirect geo-referencing is employed by using ground control points. Software such as Agisoft Photoscan is able to create highly accurate geo-referenced 3D point clouds, DSMs, and orthophotos.	Liu *et al.*, 2020
	CloudCompare with an M3C2 plugin can accurately detect volume differences and apply change detection accurately. Other methods of change detection are also possible, such as DEM of difference (DoD).DoD calculates the difference between two DEMs, allowing the volumetric changes to be estimated.	Esposito *et al.*, 2017 Xiang *et al.*, 2018
Underground mining	UAVs can be used to explore the shape, condition, and surface mineralization of mining voids. Underground UAV applications are limited, since UAVs rely on GPS signals for autonomous navigation, and GPS signals cannot penetrate the depths required for most underground mines.	Ren *et al.*, 2019
	Multi-rotor UAVs are the only type used in underground mining applications. The environment is usually narrow and cluttered and visibility is poor. Furthermore, the need to avoid obstacles, owing to the presence of stationary and moving objects, creates a significant challenge.	Scannapieco, Renga and Moccia, 2015
	Synthetic aperture radar (SAR), radar interferometry, and millimetre-wave radar could overcome the challenges imposed on UAVs by underground environments.	Scannapieco, Renga and Moccia, 2015
	Simultaneous localization and mapping (SLAM) is a promising technique for independent navigation. SLAM simultaneously builds 3D models and enables navigation in the surrounding area. Acoustic, passive, active electro-optical, or radar sensors are typically used.	Rochala *et al.*, 2019
	A visual-inertial sensor was tested to improve the localization of UAVs in dynamic underground environments. Results indicated that the system was effective, and could be integrated into future work on real UAV platforms.	Li *et al.*, 2020
	Static images can be used to determine mineralogy by visual imaging, using machine-learning algorithms and XRF signatures.	Rahman *et al.*, 2016
	Thermal, multispectral, and RGB sensors can create LiDAR geo-referenced 3D point clouds to map and investigate adverse discontinuities in underground mining excavations.	Turner, MacLaughlin and Iverson 2020

Subsidence detection

Although mining has its economic benefits, it has repercussions on the natural environment. Damage to land is evident where open-pit mines leave large voids behind after operations cease (Ren *et al.*, 2019). The impacts of underground mining are less visible, but tend to manifest as surface subsidence (Zhao *et al.*, 2020). Predicting mining-induced subsidence is seen as the basis for implementing proactive measures to reduce its effect (Dawei *et al.*, 2020). Traditional subsidence mapping is prone to data gaps and errors owing to the inaccessibility of surveyed areas, safety issues, and human error. Thus the use of remote-sensing-enabled UAVs to gather information on dangerous and inaccessible areas is highly attractive.

Several studies have considered the use of UAVs for subsidence detection, and highlighted their ability to provide centimetre-scale accuracy from autonomous flight missions. Both fixed-wing and multi-rotor drones have been employed for this purpose. Fixed-wing UAVs are mostly used where large areas have to be mapped, while multi-rotor UAVs are used for smaller areas where high resolution is required (Suh and Choi, 2017). Photogrammetry is the most often-used method, but multispectral imaging and LiDAR scanning are also employed. Suh and Choi (2017) utilized an autonomous multi-rotor UAV to obtain digitally geo-referenced orthophotographs and DTMs to calculate the position, area, and volume of an identified surface subsidence. They emphasized that UAV photogrammetry cannot fully replace traditional methods, which provide subsidence data such as horizontal ground relaxation and crack detection.

Rauhala *et al.* (2017) used fixed-wing UAV photogrammetry SfM to detect surface displacement on mine tailing facilities. Annual topographical models were used to detect the displacement over the years, and ground checkpoints were used to confirm the accuracy of that information. DoD was used to quantify the ground displacement between individual models. The study found that the models produced by UAV photogrammetry were sufficiently accurate to track surface subsidence of the tailing facilities to a decimetre scale. To obtain information on mining-induced subsidence on cultivated land, Hu and Li (2019) used a multi-rotor UAV equipped with a digital camera to develop vegetation index maps, using characteristic spectral values within the RGB bands. Multispectral and hyperspectral cameras can be employed for higher accuracy vegetation index maps, but the sensors are more costly than standard digital cameras. Zhao *et al.* (2020) and Ren *et al.* (2020) used multispectral-enabled UAVs to measure damage to land caused by surface subsidence. Ren *et al.* (2020) focused on an above-ground biomass (AGB) measurement of the health of maize crops, while Zhao *et al.* (2020) used soil and plant analyser development (SPAD) to measure and determine the effect of subsidence on corn crops. Both studies indicated that multispectral-enabled UAVs are useful tools for assessing the impact of surface subsidence on reclaimed land.

Ćwiakała *et al*. (2020) studied mining-induced subsidence using traditional field measurements as reference models, to assess UAV photogrammetry's accuracy. Their study also focused on determining horizontal terrain displacements. Both fixed-wing and multi-rotor UAVs were employed in the survey, which showed that UAV photogrammetry could be used to assess the state of surface subsidence. However, the study founded that vegetation coverage was a limitation because it distorted the accuracy of the images. Similar studies by Dawei *et al*. (2020) and Stupar, Rošer, and Vulić (2020) concluded that UAV photogrammetry offers valuable information about subsidence detection and monitoring in a short time-frame without exposing personnel to dangerous environments. Technology, therefore, is highly suited to this application.

Summary of results

Underground mining is the most challenging application for remote-sensing UAVs: it poses implementation challenges, and requires a different navigation and communication architecture to that in the UAVs used for surface mining applications. AMD monitoring, exploration, and radiological contamination mapping are specialized applications, since they need unique sensors. The need for compatibility of the sensors with the limits of a UAV's payload contributes to the slow adoption of these applications. A gap was identified in the case of structural inspections in the mining industry. This application is well-known in the building and construction industries, but the potential for use in mining operations has not been fully realized. Overall, remote sensing has several uses in mining, as discussed in the literature review. A summary is provided in Table II.

Photogrammetry is the most widely used remote sensing technique, accounting for 67% of all applications discussed

Table II

Remote-sensing UAV applications and uses per mining phase

Mining phase	Aapplication category	Application
1. Exploration	Exploration mapping	Ferromagnetic mineral identification
		Mapping variations in mineral composition
		Area geological interpretation
2. Development	Structural inspections	Infrastructure inspections
		Construction process monitoring
3. Exploitation	Blasting analysis	Fragmentation analysis
	Disaster management	3D models of disaster areas
		Change detection in disaster zones
		Disaster response missions
	Air quality monitoring	Operational air quality monitoring
		Coal fire detection and monitoring
	Geo-assessments	Assessment of inaccessible areas
		Geo-hazard identification
		Updating of geological model
	Heat detection and monitoring	Coal fire detection and monitoring
		Overheating of equipment/facilities
	Slope management	Slope failure prediction
		Slope failure appraisal
	Topographic survey	Resource and reserve estimation
		Mine planning
		Reconciliation
	Volume measurement	Mine planning
		Legal reporting requirements
		Change detection
	Underground mining	Geo-assessments and mineralogical classification
		Disaster response missions
		Gas detection
4. Reclamation	AMD monitoring	AMD detection and monitoring
	Radiological contamination	Isotopic fingerprinting and radiological contamination mapping
	Restoration monitoring	Change detection of surface condition and ecology
		Land cover recultivation monitoring
	Subsidence detection	Subsidence detection and monitoring

in the literature review. There is a significant gap between photogrammetry and other applications. Hyperspectral and multispectral remote sensing each account for 9%, followed by remote gas sensing at 6%. The adoption of photogrammetry is mainly a result of advances in the sensors utilized and in post-processing of data obtained from the UAV flight. The cost-effectiveness of digital cameras has increased leading to a significant improvement in quality image. Furthermore, the decreased size and weight of digital cameras has allowed photogrammetry using UAVs to be rapidly and broadly adopted. Advances in tilt imaging systems on UAVs, known as gimbals, enable images to be acquired from any angle without distortions from the drone's movements. Image post-processing is advanced with the SfM algorithm, allowing for the rapid development of any model that is required. Two software applications were prominent in the literature: Agisoft Photoscan and Pix4D, both of which use SfM algorithms to produce highly accurate photogrammetric models.

Other software applications, such as CloudCompare and ShapeMetrix, use the developed models for further analysis. The models can be used in CAD software to update existing geological models with geo-assessments. Algorithms such as DoD, SLLAC, and SDA also use photogrammetric data to determine aspects such as slope movement, displacement, and volume change.

Adoption of remote sensing techniques such as radiological and magnetic remote sensing is limited owing to the specialized nature of the sensors required for specific applications. The size and weight restrictions of UAVs and the high cost of sensors contribute to the slow adoption of hyperspectral, multispectral, LiDAR, and TIR remote sensing techniques. Table III provides a summary of the studies that have evaluated a specific sensor for a specific application and mining phase. Some studies evaluated more than one sensor.

The review identified the following potential benefits of remote sensing aerial vehicles within the mining industry.

- ➤ Improved time-efficiency (Kirsch *et al*., 2018)
- ➤ Improved geological interpretation (Kirsch *et al*., 2018)
- ➤ Reduced costs (Kirsch *et al*., 2018)
- ➤ Spatial coverage (Kirsch *et al*., 2018; Heincke *et al*., 2019)
- ➤ flexibility (Kirsch *et al*. 2018)
- ➤ Semi-autonomous flights for visual and 3D inspections (Pinto *et al*., 2020)
- ➤ Assess ment of difficult areas and safe and fast inspections (Pinto *et al*., 2020; Said *et al*., 2020; Ren *et al*., 2019; Francioni *et al*., 2015; Leo Stalin and Gnanaprakasam, 2020; Borbinha *et al*., 2020)
- ➤ Monitoring progress to determine whether activities are effective (Said *et al*., 2020)
- ➤ Assessing the impact of surface subsidence (Ren *et al*., 2020; Zhao *et al*., 2020; Dawei *et al*. 2020; and Stupar, Rošer, and Vulić, 2020).

Conclusions

This SLR aimed to review the status of academic publications in the field and to answer the following two research questions:

1. Which applications of remote-sensing UAV technology are used in the four phases (exploration, development, exploitation, and reclamation) of mining?
2. Which types of UAV and remote sensing methods are typically used in these applications?

The SLR employed a methodology that identified 72 quality documents on the subjects of remote sensing, UAVs, and mining. A total of 15 applications were identified and synthesized in the four mining phases. The different remote sensing techniques and UAV types were considered for each application type. Most of the research reviewed the exploitation and reclamation phases of mining, with only limited applications identified in the exploration and development phases. Opportunities exist, therefore, to expand remote-sensing UAV applications in these phases. Photogrammetry was the most popular technique by

Table III

Remote sensing sensor studies per application type and mining phase

Mining phase	Application	Sensors							
		Multispectral	Gas	Radiological	Magnetic	LiDAR	TIR	Hyperspectral	Photogrammetry
1. Exploration	Exploration mapping				1			2	2
2. Development	Structural inspections								1
3. Exploitation	Blasting analysis								1
	Disaster management		2			1			
	Air quality monitoring		4						
	Geo-assessments							1	10
	Heat detection and monitoring						1		1
	Slope management					1			11
	Topographical survey	1						1	14
	Volume measurement								6
	Underground mining	1				1		1	2
4. Reclamation	Acid mine drainage monitoring	1						1	1
	Radiological contamination			1					
	Restoration monitoring	4				1	2	2	13
	Subsidence detection	2				1		1	7

far. Other remote sensing techniques are limited because cost-effective, lightweight, and compact sensors are not yet available. There has been some progress in hyperspectral, multispectral, and LiDAR sensors, but they remain costly and are not entirely suited to UAV implementation. Researchers in the field could use this review to identify gaps in published research and potential collaborators. Stakeholders from the mining industry could use this review to identify relevant applications for opportunities for implementation, improvement, and innovation. Future research may aim to compare the status of academic publications with that of industry developments or patent applications.

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