Ecological Questions 35 (2024) 4: 69–90 http://dx.doi.org/10.12775/EQ.2024.049

Comprehensive review of unmanned aerial vehicle application to safety mining management

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Received: 23 April 2024 / Accepted: 21 May 2024

Abstract. The increasing interest of users in unmanned aerial vehicle (UAV) technology has developed new fields of application for it. Presently, UAVs are working in so many areas and the mining industry has shown grown interest in the use of UAVs for routine operations in surface, underground mines, and mine waste dumps. In this paper, a thorough review has been performed on the application of UAVs in mine safety management. Systematic reviews were conducted to summarize the results of over 60 papers published during the 2010-2021 period. The study offers a review of the most common applications involving mine safety, the styles of flying control, and the UAV types exploited. The paper also contributes to the identification of prevalent data acquired by sensors and points out the most popular processing techniques of aerial imagery. The obtained results revealed that UAVs are used at mining sites for safety purposes including mine surface displacements, stability monitoring, working environment, coal fire identification, drill and blast, and mine waste dump operations. This research hopes to provide a technical reference, expanding the knowledge and recognition of UAV monitoring to manage mine safety, as well as an assessment of applications in mining activities.

Keywords: aerial imagery, UAV, Drone, Mine, mine safety, mine safety management, monitoring.

1. Introduction

Unmanned aerial vehicles (UAVs) are becoming popular and are being used for various applications at an accelerating rate (Liu et al., 2020). By UAV in the current study we mean the actual aircraft that flies around to collect the required data and imagery. The increasing interest of users in the UAV technology has developed new fields of application for it. Many advantages, such as low cost, short revisiting cycle, flexibility, and high accuracy, have made UAVs powerful tools in many fields. As is known, the manufacturing sector of developing countries, especially in the iron and steel, aluminum and mining industries, requires constant monitoring to ensure environmental and worker safety (Ayeleso et al., 2024; Kruzhilko et al., 2024). In recent years, UAVs have been deployed for various sectors including agriculture (Tsouros et al., 2019), disaster management (Restas, 2015), construction (Tatum & Liu, 2017), environmental monoitoring (Medvedev et al., 2020), smart city applications (Khan et al., 2018), mine industry (Park & Choi, 2020), etc. Presently, the mining industry has shown grown interest in the use of UAVs for routine activities such as geological and structural analysis (Jakob et al., 2016), aerial geophysical survey (Parshin et al., 2018), topographic surveying (Gil & Frąckiewicz, 2019), monitoring of soil pollution (Fang et al., 2019), monitoring of ecological restoration (Lee et al., 2016), etc. In addition to the studies focusing on solving specific problems in the mines using UAV technology, many articles have reviewed the application of UAVs in the mining sector in general. Lee and Choi categorized the applications of UAVs in the mining industry, consisting of surface, underground, and abandoned mines (Lee & Choi, 2016). Park and Choi reviewed academic papers on the applications of UAVs in mining by classifying the mining process into three phases: exploration, exploitation, and reclamation (Park & Choi, 2020). According to Ren et al. (2019), the application of UAVs remains to be further explored for complex mining environments. They presented research results from applications using the more advanced UAV platforms and sensors in the monitoring of mining areas. It can be seen that UAVs show great potential in mining monitoring at small or large scales (Ren et al., 2019). Besides reviewing the previous articles, Shahmoradi et al. (2020) explored information from companies that provided UAVs for the mining industry. The authors discussed various applications of UAVs in mine activities, such as ore control, rock discontinuities mapping, 3D mapping of the mine environment, blasting management, post-blast rock fragmentation measurements, and monitoring the stability of tailings dam. In addition, the UAV applications in the mining industry for search and rescue missions were included in their study (Shahmoradi et al., 2020). Although many applications of UAVs have been considered in mining, most of the above studies have not mentioned much about mine safety using UAVs which is paramount in the mining environment. To fill this gap, this paper reviewed UAV applications in mine safety, we formulated the following research questions:

Q.1.Which are the different types of UAV applications in mine safety management?

In this research question, we aim to explore the current trends in the application of UAVs in mine safety. In this question, we provide a thorough description of the different types of applications that UAVs can support based on the different activities of mining safety management.

Q.2. Which UAV system technologies are adopted in mine safety management?

In this research question, we identify the system characteristics of UAV-based applications for mining safety management.

Q.3. What types of data can be obtained by UAVs?

In this research question, we record the various kinds of data that can be acquired by UAVs based on the sensor technology employed. In order to do this one, the authors introduced different data types that can be used in mine safety control, mainly belonging to three types: visible image, thermal infrared image, and dust data.

Q.4. Which data processing method and software can be used to exploit the data acquired by UAVs for mine safety management?

In this research question, we identify the methods that are used for image analysis in mine safety management. We distinguish between three types of data processing methods that can be used alone or complementary to gain insights regarding a field namely: (a) Photogrammetric techniques; (b) Machine Learning techniques; and (c) Other indices. Furthermore, the most commonly adopted software solutions in the works involving mine safety reviewed to support and accelerate the data analysis procedure are summarized in this study.

Q.5. What methods of flying control have been used for UAV applications in mining?

In this question, we detected the methods of flight control of UAV-based applications for mine safety. Through answering this research question, the methods of flying control could be determined as manual, autonomous, and semi-autonomous.

2. Materials and Method

To answer these research questions, we reviewed 40 recent papers published during the 2010–2021 period. Figure 1 shows the process of the literature search and classification of UAV applications in mine safety. The research methodology adopted in the paper consists of four following steps:

a) Select databases: The literature was retrieved from Scopus, Web of Science, Google Scholar, and Science Direct;

b) Filter the databases with the terms "UAV OR Drone", "safety", and "mine or mine industry or mine activities" in the topic, title, abstract, or keywords. Time restriction filters were not used;

c) Read the paper to confirm the relevancy of the papers;

d) Classify papers as the purpose of the applications in mine safety: The categorization approach, year of publication, and purpose are recommended by the authors of this paper. The publications are sorted into categories for specific purposes based on the authors' experience over the related

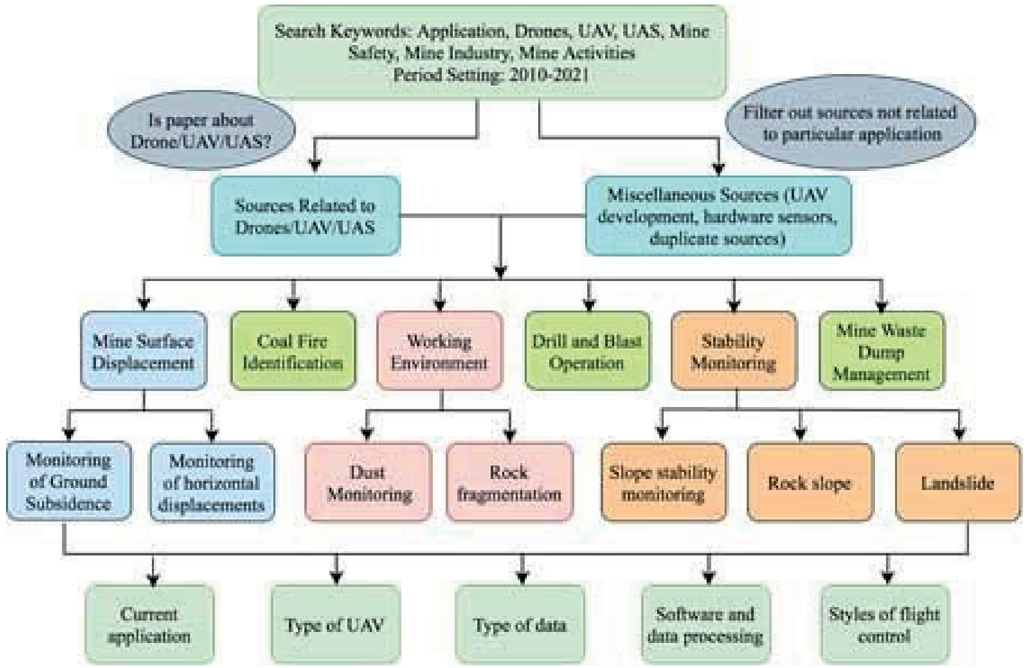

Figure 1. Process of the literature search and classification of UAV applications in mine safety

papers and each paper was classified in only one type of purpose.

3. Application UAV in safety management in mines

Utilizing UAVs helps prevent unnecessary accidents by detecting dangerous hazards and identifying new sources of danger. The most common applications of UAVs for mine safety management, as recorded in the literature, are the following:

- Mine surface displacement;
- Stability monitoring;
- Working environment;
- Coal fire identification;
- Drill and blast operation;
- Mine waste dump management.

3.1. Determining mine surface displacements

3.1.1. Monitoring of ground subsidence in mining areas

Subsidence plays crucial role in the safety of mining operations, constructions above the underground faces (Hosseini Alaee et al., 2019). Continuous investigation of improvements in observing mine subsidence is done in order to increase security and reduce costs. There are the dangers of mine subsidence that human must face. Infrastructures around the mine subsidence area can get destruction, further exploration of coal reserves may be impeded, and subsidence may create new routes for oxygen to enter the subsurface and flare up old fires or cause new fires. In addition, mine subsidence may injure or kill workers during mining activities. Based on instrumentation, monitoring, and analysis of possible influences the mine subsidence can be prospected. However, human-based subsidence mapping and surveying methods suffer from errors, omissions, and missing related to data because of accessibility, safety, and manual digitization (Suh & Choi, 2017). Also, for safety reasons, it is highly challenging for humans to investigate and monitor regions where mine subsidence occurs. Therefore, the importance of using UAVs to conveniently acquire data in inaccessible areas is increasing. This method enables accurate, quick, low-priced, and safe surveying and mapping, which supplements traditional surveying technology in areas of mining subsidence (Park & Choi, 2020). In this paper, the UAVs were used to monitor the tailings dams and subsidence areas that originated because of mining.

Monitoring of ground subsidence is performed in all types of mines. While Suh and Choi (2017) mapped hazardous mining-induced sinkhole subsidence in a abandoned mine (Suh & Choi, 2017), Ge et al. (2016) established a mine subsidence map of underground mining in New South Wales, Australia. The authors provided the outcomes of the work carried out using UAVs in the Ulan open-cut mine and Tahmoor underground mines. They used a UAV to determine the volume of the stockpile, monitor the safety of highwall slopes, and establish the underground mine subsidence map in these mines. There are three ways to observe mine subsidence such as UAV technology, total station, and laser imaging detection and ranging (LIDAR) measurements. Findings indicated similar precision between the methods but high-resolution images taken by UAV and processed by digital surface models (DSM) were much more practical and faster (Ge et al., 2016). Underground mining causes numerous threats to the environment and people. One of such threats is terrain surface deformation, which is especially dangerous in urbanized areas because it can result in severe infrastructure damages. For this reason, it is indispensable to conduct systematic monitoring of the terrain surface deformations in the vicinity of the mine. Monitoring of terrain vertical deformations caused by underground mining using UAVs can be found in (Dawei et al., 2020; Ignjatović Stupar et al., 2020). In 2020, some scientists conducted research to assess the role of UAV technology in mine subsidence monitoring. Dawei et al. (2020) concluded that the UAV approach can obtain the surface dynamic subsidence basin of coal mining regions in a short time with credible factors of mining subsidence. In study (Ignjatović Stupar et al., 2020), UAV photogrammetry technology was used to determine the surface dynamic subsidence basin generated by underground coal mining and calculate factors of mining subsidence in the short term in the Wangjiata coal mine in Inner Mongolia of China. Figure 2 shows the schematic diagram of monitoring surface subsidence caused by coal mining using UAV Photogrammetry technology. They employed the measured subsidence value of the UAV to inverse the probability integral parameters. This method provided more comprehensive measured data and precise predicted parameters for mining subsidence (Dawei et al., 2020). Besides, some experts proposed a method where photogrammetric measurements obtained by UAV technology were introduced through a 3D point cloud to estimate subsidence (Pal et al., 2020; Jóźków et al., 2021). In the study of Ignjatović Stupar et al. (2020), the accuracy of determining subsidence in the Velenje coal mine using UAV was verified through Global navigation satellite systems (GNSS) real-time kinematic and total station tachymetry. The introduced method contributes a foundation for further studies of surface subsidence on underground excavations where mine reclamation implements simulations as excavation progresses (Ignjatović Stupar et al., 2020). Similarly, Pal et al. (2020) conducted cloud-to-cloud analysis to determine the surface subsidence. This prognosis model gave only the prediction of subsidence from geometric and volume loss perspectives. A 3D point cloud comparison was also done to observe the intensity of the subsidence and detect sinking holes or regions of soil dumping. The obtained results revealed that the proposed method provides a basis for further research of surface subsidence above underground excavations where terrain reclamation carries out simulations as excavation progresses (Pal et al., 2020). In addition to utilizing 3D point cloud, UAV-based surface models such as DTMs (Digital terrain model) and DEMs (Digital Elevation Model) used to detect and measure the terrain deformations caused by underground mining (Dawei et al., 2020) as well as deformations in the excavation area and surroundings of a marble quarry (Yavuz, 2019). Jóźków et al. (2021) used UAV and LiDAR data to investigate the vertical variations of the mining areas. The analysis results revealed that compared to UAS LiDAR sensors, UAS photogrammetry provides less noisy data and more accurate findings for measuring terrain subsidence. It should be emphasized that by UAS in the current study we mean the entire package needed to operate the system, which includes the UAV itself, the ground control system, camera, GPS, all the software, skills needed to operate the system and tools required for maintenance. Moreover, the conducted experiments showed that it is possible to identify medium-scale deformations through UAV photogrammetry. However, the investigations need to be carried out in the non-vegetated areas and the data should not be acquired during the growing season to keep its best quality (Jóźków et al., 2021). Additionally, scientists established the deformation map of a marble quarry found in Eliktekke village in Amasya province, Turkey. This map was produced from orthophoto and DEMs obtained from flights completed at certain intervals with the UAV. Determination and observation of deformations that can form in open-pit mines have great importance in terms of safety and continuation of production (Yavuz, 2019).

In short, as a new monitoring approach for mining subsidence, UAV photogrammetry technology overcomes some limitations such as long data collection time, high labor force and intensity, burying fixed measuring points, and difficult preservation in traditional observation stations. Moreover, it can determine ground dynamic subsidence basin data in mine areas in a short time.

3.1.2. Monitoring of horizontal displacements caused by mining

Analyses of the suitability of data acquired from UAVs to determine horizontal displacements caused by underground mining are very rare. Underground mining activities result in displacements and deformations of the land surface, which may pose a threat to building structures. Although horizontal displacements are usually not very large (only more than a few decimeters), these movements should be monitored to assess and minimize their harmful influences. In order to achieve this, with the aid of UAV-based ultra-high-resolution orthomosaics (less than 2 cm/pix), Puniach et al. (2021) established a workflow for automatically determining

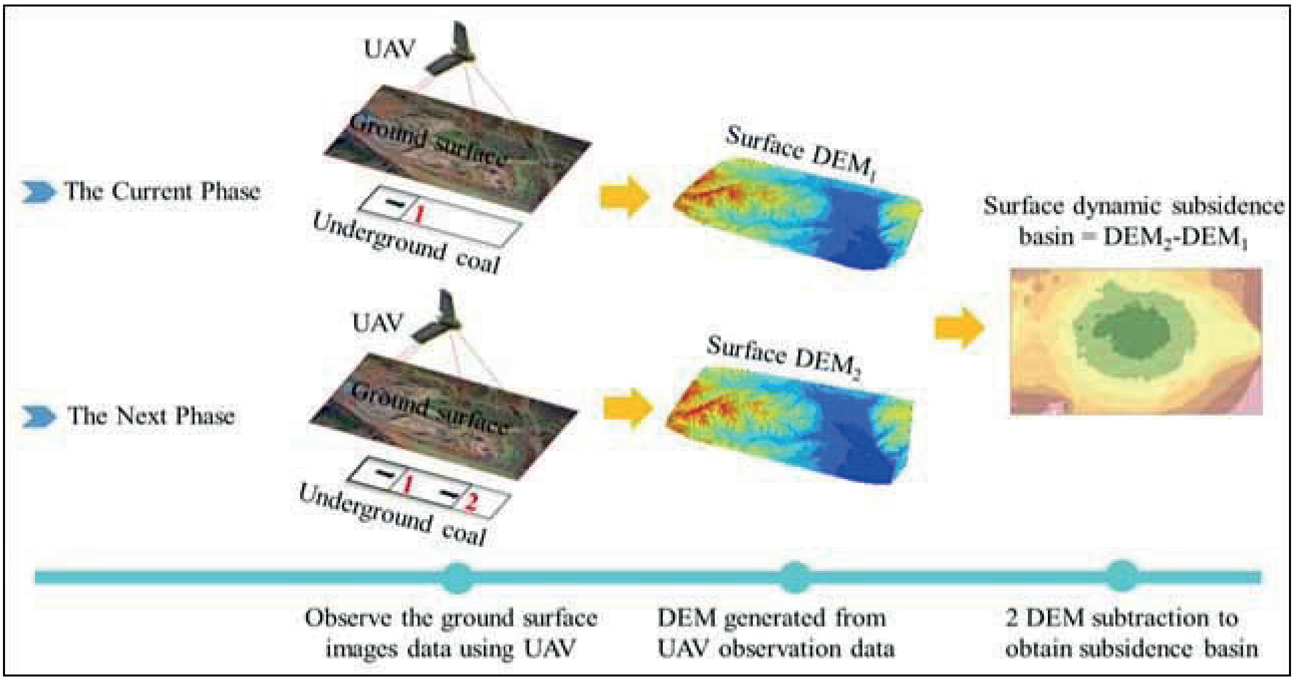

Figure 2. Sketch of UAV Photogrammetry technology for monitoring surface subsidence caused by coal mining (Dawei et al., 2020)

the vector field of horizontal displacements brought on by underground mining. Accuracy was measured against manual displacements based on orthomosaics created by UAVs and against displacements independently calculated using terrestrial laser scanning. Moreover, the authors indicated that the accuracy depends on the resolution of the analyzed images and it usually takes values not exceeding the size of two pixels (in this study, resolution of images is from about a few decimeters to several meters). Therefore, the use of UAV-based photogrammetry to determine horizontal displacements allows obtaining the displacement field at a level of accuracy which is sufficient in practice to determine model parameters and to monitor the phenomenon on an ongoing basis (Puniach et al., 2021).

The high potential of UAVs has also been noticed in determining land surface displacements, including those caused by underground mining. Pawel et al. (2020) presented a case study illustrating the application of UAV photogrammetric data to determine land surface deformation in areas affected by underground mining in Poland. Horizontal displacements are calculated through points of observation lines created in the field for monitoring purposes, as well as based on scattered situational details. Figure 3 shows values and directions of horizontal displacements in the form of vectors determined based on the identification of characteristic situational details. In addition, numerous types of discontinuous deformations are detected and their development over time is presented. The obtained results are compared for prediction of the land deformations. After the data processing, it can be estimated that the accuracy of the calculation of XY coordinates and the horizontal displacements in the best situation is about 1.5–2 cm Ground Sample Distance (GSD), and the range 2–3 cm GSD for heights and subsidence (Ćwiąkała et al., 2020).

In brief, UAV technology can be treated as another tool available for monitoring surface geometries and their variations, especially as it allows the acquisition of mine surface data. This methodology was applied to determine many key parameters associated with the current state of horizontal displacements caused by underground mining operations. Table 1 summarizes the reviewed literature on UAV application to monitor ground subsidence and horizontal displacement in mine areas. Almost all studies detected surface displacement in the underground mines, while only one paper was applied for the open-pit mine and one article analyzed in the abandoned mine.

3.2. Stability monitoring

UAVs are also frequently used for monitoring stability including slope stability, rock slope, and landslide. One of the main challenges in mining activities is obtaining geotechnical data from difficult or inaccessible areas. Based on terrestrial LiDAR methodology, mapping discontinuity for slope stability could be generated. In this method, because of the small scan angle of LiDAR technology, "shadow zones" or

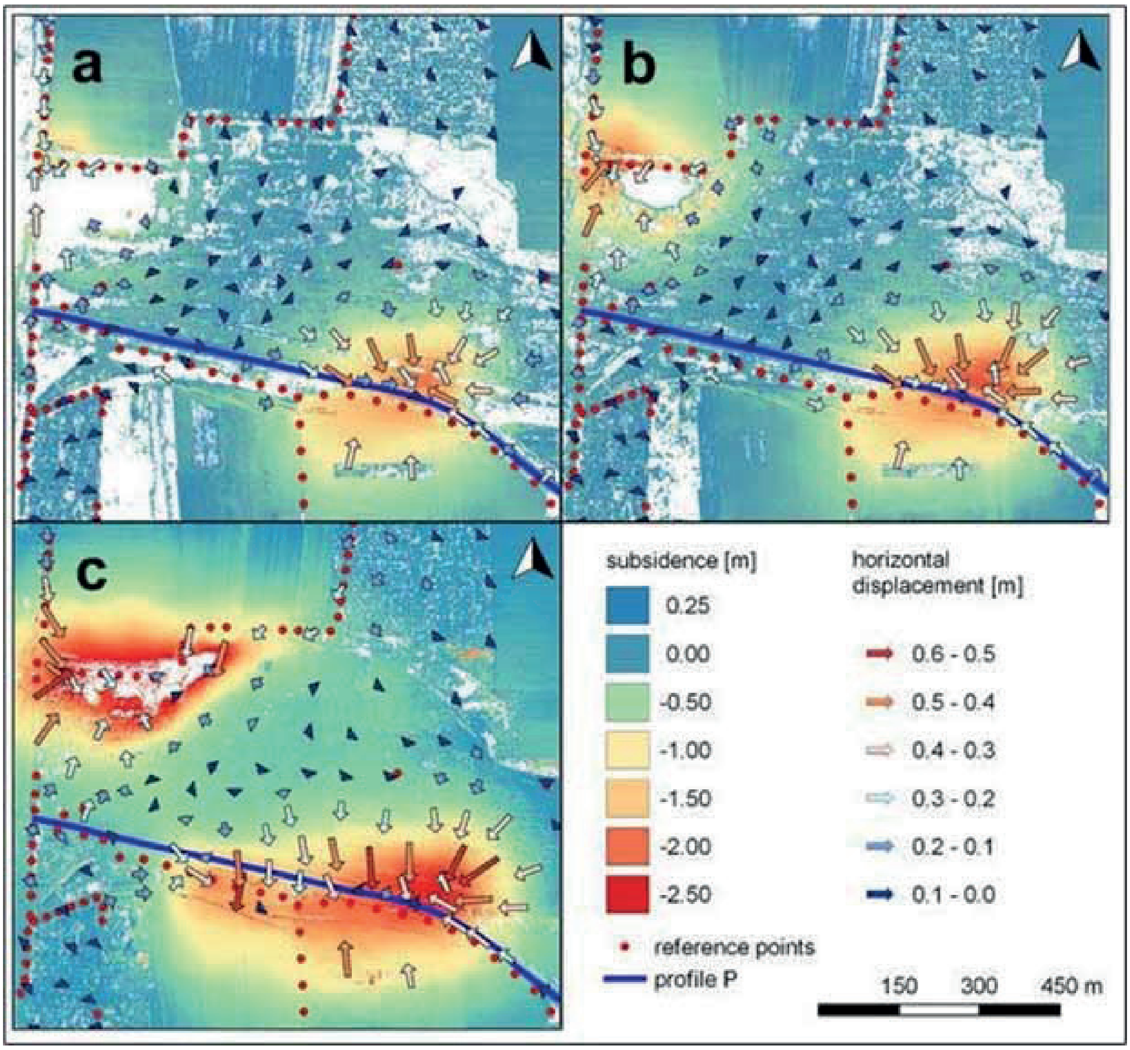

Figure 3. Displacements determined using UAV photogrammetry at the Piekary site during: (a) 03.2016–09.2016, (b) 03.2016–11.2016, and (c) 03.2016–04.2017 (Puniach et al., 2021)

data gap is repeatedly created. Today, UAVs can be employed to take photos and make observations by analyzing the overlapping photographs (Shahmoradi et al., 2020). UAVs can be used for rock slope analyses (including the stability and discontinuity analysis of rock slopes that are difficult to access directly) and lithological classification of rock masses (Park & Choi, 2020). All the literature reviewed in this paper used UAV-based images to map the highwall, analyze the characteristics of the slope, and survey the landslides.

3.2.1. Slope stability monitoring

The safe operation of the surface mines and the safety of the employees' lives are influenced by slope stability. The loss caused by slope disasters can be decreased with effective evaluation of slope stability (Zhang et al., 2021). Slopes in surface mines are excavated at the steepest possible angle to maximize profitability, which increases the danger of failure. UAVs are emerging as a useful approach to acquire images with a high spatial resolution which provide fast and accurate qualitative results that can be used for stability analysis. Ge et al. (2016) reported the obtained results indicated that UAVs have potential in observing the highwall slope stability. The authors gave the results implemented by using UAVs in the Ulan open-cut mine and Tahmoor underground mines in New South Wales (NSW), Australia. They used a UAV to monitor the safety of highwall slopes in these mines (Ge et al., 2016). A slope stability analysis of the mines can be completed using surface models generated from UAV images such as DEM (Vemulapalli & Mesapam, 2021), 3D models (Vemulapalli & Mesapam, 2021; McLeod et al., 2013; Nagendran & Ismail, 2020), DTM (Buill et al., 2016; McLeod et al., 2013). Vemulapalli and Mesapam used the acquired images from the UAV to produce DEM. Factors of slope instability derived from DEM such as slope, drainage density, geological, aspect along with inventory maps are provided as an input data to Artificial Neural Network (ANN)

Table 1. Summary of UAV applications for determining mine surface displacements

Purposes	Position	Application	Refer-ence	UAV type	Acquisi-tion Data Image	Software	Data processing	Flight control style
Monitoring of Ground Subsidence	Abandoned mine	Generation of subsidence inventory	(Suh & Choi, 2017)	Rotary wing	Digital Camera Image	PIX4D maper	Photogrammetry techniques	Autonomous
	Undergro-und	Mapping the underground mine subsidence.	(Ge et al., 2016)	Unknown	Digital Camera Image	Unknown	Photogrammetry techniques	Unknown
	Undergro-und mine	Observing of terrain vertical deformations caused by underground mining	(Jóźków et al., 2021)	Fixed-wing	RGB image	Agisoft	Photogrammetry techniques	Autonomous
	Undergro-und	Determining of surface dynamic subsidence basin induced by underground mining	(Dawei et al., 2020)	Fixed wing	Digital Camera Image	PIX4D maper	Photogrammetry techniques	Autonomous
	Undergro-und mine	The sudy presented a meth-odology for determining mine subsidence over Velen-je coal mine through UAV	(Ignjatović Stupar et al., 2020)	Rotary wing	Digital Camera Image	3D Survey aerial image processing	Photogrammetry techniques	Autonomous
	Undergro-und mine	Proposing photogrammetric observations obtained by a UAV system to predict active subsidence in the coal mine Velenje through a 3D point cloud	(Pal et al., 2020)	Unknown	Digital Camera Image	3D survey	Machine learning method	Unknown
	Open-pit mine	Observation of deforma-tions with UAVs in open pit operations	(Yavuz, 2019)	Unknown	Digital Camera Image	Pix4D maper	Photogrammetry techniques	Manual
Horizontal displa-ceme-nt	Undergro-und mine	Determination of horizontal displacement caused by underground mining	(Puniach et al., 2021)	Fixed wing	Digital Camera Image	Agisoft Metashape	Machine learning method	Autonomous
	Undergro-und mine	Shows how UAV data can be used to monitor land surface deformation in areas affected by underground mining.	(Ćwiąkała et al., 2020)	Fixed-wing	Digital Camera Image	Agisoft Metashape	Photogrammetry techniques	Autonomous

models. The criteria are assessed based on the role of each of them in inducing slope failure (Vemulapalli & Mesapam, 2021). Also carrying out the slope stability assessment in the open-pit mines, McLeod et al. (2013) studied the feasibility of obtaining a 3-D point cloud from video images acquired with a UAV using Structure from Motion (SfM) photogrammetry software. In this study, a lightweight vertical take-off and landing UAV with a miniature video camera is used. Accordingly, fracture orientations were measured successfully through 3D aerial photographs (McLeod et al., 2013). In addition to slope stability monitoring of surface mines, UAVs are great tools for evaluating the quarry slope deformations. Buill et al. (2016) has performed capturing data from UAVs (video and photo), and from the ground (photo) in the fronts of a quarry located in the region of El Garraf. In this study, photographic images or 4Kvideo acquired from UAVs were used to track unstable slopes and evaluate destruction after the events and control of infrastructure affected. The obtained indicated that most families of cracks, or rockfall scar size distribution of a cliff can be determined by the highly accurate and quality DTM (Buill et al., 2016). The use of UAVs for a remotely piloted survey enables the replacement of the surveys undertaken with traditional method in quarries. Nagendran and Ismail (2018) presented the application of drone mapping for quarry observation and slope assessment. The quadcopter was used to acquire both aerial and side images for slope assessment. Image captured were processed employing a photogrammetry software, Agisoft Photoscan to produce the final output that consists of orthophoto, digital surface model, 3D dense pint cloud, and 3D model. Figure 4 below depicted the outcome of rock slope mapping. The slope

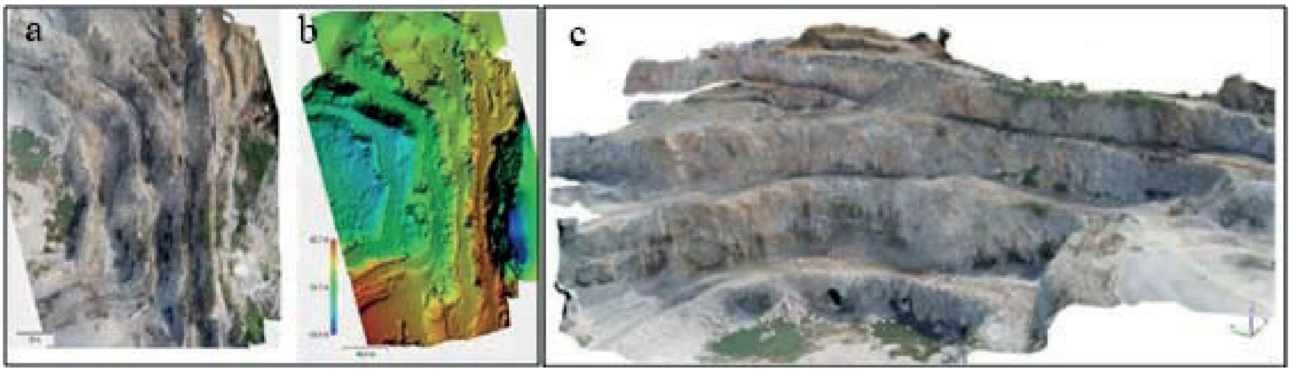

Figure 4. The outcome of rock slope mapping (a) Orthophoto (b) DSM (c) 3D model of rock slope (Nagendran & Ismail, 2020)

stability assessment computation was done using facet extraction to detect the major discontinuity sets for rock slope stability analysis (Nagendran & Ismail, 2020).

3.2.2. Rock slope stability analysis

Rock slope stability is defined as a process whereby slopes are stabilized against the possibility of instability for both cut and natural slopes (Kamaruszaman & Jamaluddin, 2016). The exploitation activity can cause various types of instabilities in open pit quarries, especially when the development schemes do not depend on scientific processes (Gadri et al., 2015). Identifying the rock slope stability of quarry have been mentioned in many studies. According to Anua et al. (2020), the mechanics of instability depend commonly on the nature, strength, and structures of the rock mass. Therefore, they used the UAV approach to identify the structure of rock mass and determine the stability of the selected quarry face. To achieve this, photogrammetric mapping and kinematic analysis were performed consequently at Hume Cement Quarry, Gopeng for safety purposes. The result indicated that UAV technology can be used in many sectors and there are many advantages in applying the UAV approach to determine the stability of rock slope (Viana et al., 2019). Mine slopes are inherently unstable structures that can result in the losses of peoeple, property, and equipment as well as the abrupt cessation of mine operations. They depended on field stress, degree of chemical weathering, interruption properties, slope geometry, groundwater, lithotypes, seismic loadings and blasting. Among these criteria, discontinuities are the most affectting factor on rock slope instabilities. Hartwig and Moreira (2021) described the integration of different techniques of rock mass characterization for slope stability assessment in the Itaoca district. They used UAV images with a high spatial resolution for structural analysis and as a georeferenced base-map, and kinematic slope stability analysis. The obtained results have shown that drone photos can actually aid in the structural characterization of rock masses since they make it possible to classify different levels of fracturing and to identify structural domains along the entire slope surface (Blistan et al., 2016). According to Viana et al. (2019), natural rock masses present different geological ricks. Therefore, it is necessary to establish a 3D model of the quarry wall to analyze the stability of the rock slope. They described the application of drones in generating the 3D model of the Jardim Garcia quarry using Agisoft Photoscan software and imagery survey was made with a DJI Phantom 4 Pro drone, for which the flights were planned with the Litchi application. The authors found that the examination of rock slope stability was deemed to be extremely valuable because it enables more dynamic depiction of structures and the gathering of a huge amount of structural data (Viana et al., 2019). Blistan et al. also indicated that UAVs could be used to document outcrops of geological rocks, particularly those that are inaccessible in mines. In the mining region of Lehôtka pod Brehmi, Slovakia they created photogrammetry documentation by using UAVs to photograph rocks that were around 75 meters tall. The Agisoft PhotoScan software was used for image processing, and a digital terrain model of the outcrop was created. The outcomes demonstrated the possibility of employing UAVdata outputs to build a geological structure model (Blistan et al., 2016). Stead et al. (2019) depicted the application of field and remote sensing technology for the rock slope features at various scales and distances over 15 years investigated by the Engineering Geology and Resource Geotechnics Research Group at Simon Fraser University in Vancouver, Canada. They give a summary of the potential applications, benefits, and drawbacks of different remote sensing techniques for comprehensive characterizations of rock slopes. The study presented the importance of remote sensing methods, UAVs, etc. in the investigation of rock slopes (Stead et al., 2019). Utilizing a UAV for rock slope stability investigations has a number of advantages, including the ability to collect data in inaccessible locations where foliation and fractures may change their attitude and other basic geometric properties. Salvini et al., (2016) described the use of the

UAV in acquiring data for mapping discontinuities within a marble quarry. To reconstruct the quarry geometry, dense 3D point clouds produced by image processing were utilised. Discontinuities were then mapped deterministically in great detail. The findings emphasize the benefits of combining photogrammetric data with those obtained using traditional methods since the resulting understanding of the location is essential for instability evaluations requiring numerical modeling (Salvini et al., 2017). Unlike quarries, the analysis of rock slope stability by UAV in closed mines and open-pit mine rarely occurs. The application of a drone in collecting data for mapping discontinuities within a closed marble quarry can be found in (Blistan et al., 2016). In order to acquire high-resolution topographic data on a blocky rock mass situated inside a quarry susceptible to discontinuity-controlled instability processes, Salvini et al. (2018) used an AibotixTM Aibot X6 six-rotor multicopter. An exact identification and geometrical measurement of the geological discontinuities that isolate large quantities of rock were done using a detailed 3-D model of the region. The stability analysis performed using the RocscienceTM Swedge software revealed that rock bridges can significantly affect the conditions of slope stability (Salvini et al., 2018). For surface mines, aerial photogrammetry is mainly used along with machine learning algorithms for rock slope stability classification (Salvini et al., 2017), engineering geological site investigation and data collection on slopes (Beretta et al., 2019). Four categories of rocks were identified in the study of Beretta et al. on the slopes of open-pit mines: There are four groups of rocks classified in Beretta et al.'s research including diorite, granite, soil, and flora. To achieve this, they first reconstructed the terrain through aerial photogrammetry acquired by UAV. Then, they developed a point cloud to represent the mining regions. The obtained result shows the influence of the variability on any type of visual identification of lithological materials (Beretta et al., 2019). In addition, it is worth noting that the ground failure on rocky slopes is a geological hazard with potentially catastrophic effects for the deneral public or workers in the mining industry. Therefore, it is necessary to carry out geotechnical and engineering geological site investigations on slopes where are often difficult to access on foot. Bar et al. (2021) used UAVs for site investigation to categorize natural and engineered rock slopes. Obtained results demonstrated the effectiveness of this technique for generating a preliminary engineering geological model from which slope stability analyses can be derived to predict future ground behavior to assist in managing hazards associated with the geological risk (Bar et al., 2021).

3.2.3. Documentation of Landslides

Vrublová et al. (2015) employed UAV technology to document landslides and inaccessible areas of the Nástup Tušimice mine in the North Bohemian Brown Coal Basin. The images were taken by the UAVs system that automatically scans a study area. In order to capture detailed documentation of interset regions of the mine, they utilized a technique called digital terrestrial photogrammetry. An orthophoto and 3-D model of the landslide regions were created through aerial photographs taken automatically using a UAV. Thereby, a proper measurement method can be found for operational targeting of landslides and difficult-to-reach places of the mine sites (Vrublová et al., 2015).

In sum, UAV data can be useful to give an overall view of the mining sites. The orthophoto, DSM, point cloud, and 3D model obtained through image processing were used to rebuild the mine geometry. Thus, the slope stability calculation was made to detect the major discontinuity sets for rock slope stability analysis or discontinuity determination. In addition, evaluation of landslide of a mine using a UAV system is a quick and effective approach. Table 2 sums up the research on UAV application to analyze slope stability, rock slope, and landslide on the mine surface. A total of 15 documents were reviewed. Most of the literature was conducted in open-pit mines and quarries except for one study done in an underground mine and another performed in a closed mine.

3.3. Analysis of working environment

The use of a drone can improve safety compared to other surveying systems. However, the majority of drones use today in underground mining is still an area that requires significant research and development. Because the unavailability of GPS, the low light conditions, and the confined spaces, it is exceedingly problematic to utilize drones in an underground environment. In addition to taking aerial photograph, UAV can perform various tasks when installed with thermal and dust sensors, communication modules, and lights (Park & Choi, 2020). In order to increase the safety of working environment, distribute fast and real-time observing results, and minimize human exposure to unsafe underground conditions, Raj (2019) proposed a monitoring system using UAVs in underground mines where GPS is not useful, light is inadequate, and spaces are constrained. The author proposed a method for using UAVs in low-light conditions by attaching specially designed illumination to this device (Raj et al., 2019). The following articles are related to the monitoring or analysis of the working environments in mines using various sensors, therefore the safety of workers and mine monitoring equipments are improved.

3.3.1. Dust monitoring

Mining operations are accompanied by significant dust emissions, which makes working conditions hazardous

Table 2. Summary of UAV applications for stability monitoring

Purposes	Position	Application	Reference	UAV type	Acquisition Data Image	Software	Data processing	Flight control style
Slope stability monitor-ing	Under-grund mine	Monitor the safety of slopes, and map the underground mine using UAVs	(Ge et al., 2016)	Fixed Wing	Digital camera image	Unknown	Unknown	Unknown
	Open-pit Mine	Slope stability analysis using neural networks and UAV photogrammetry.	(Vemulapalli & Mesapam, 2021)	Unknown	Digital Camera Image	Agisoft	Machine learning methods	Unknown
	Open-pit Mine	Present the possibility to generate a 3-D point cloud from video images acquired by UAVs	(McLeod et al., 2013)	Rotary Wing	Digital cam-era image/ video	Visual SfM	Machine learning methods	Autonomous
	Quarry	Present the application of drone mapping for quarry monitoring and slope assessment	(Nagendran & Ismail, 2020)	Both	digital camera image	Agisoft Photoscan	Photogrammetry techniques	Autonomous
	Quarry	UAV based images used to track unstable slopes and evaluate damage after the events and control infrastructure influenced	(Buill et al., 2016)	Rotary	digital camera image/	Agisoft Photoscan	Photogrammetry techniques	Semi-Auton-omous
Rock slope	Open-cast quarry	Evaluate the stability of the limestone quarry slope for safety purposes by UAV	(Anua et al., 2020)	Unknown	Digital Camera Image	Agisoft Photoscan	Machine learning methods	Unknown
	Open-cast quarry	Describe the integration of different techniques of rock mass characterization for slope stability evaluation using UAV data	(Hartwig & Moreira, 2021)	Rotary wing	Digital Camera Image	Agisoft Photoscan	Rock Mass Rating calculation	Autonomous
	Quarry	Using a UAV derived 3D model in rock slope stability analysis of Jardim Garcia quarry	(Viana et al., 2019)	Rotary wing	Digital Camera Image	Agisoft PhotoScan	Machine learning methods	Autonomous
	Closed mine	Describe the application of a drone in obtaining data for mapping discontinuities within a marble quarry	(Salvini et al., 2018)	Fixed wing	Digital Camera Image	Agisoft PhotoScan	Machine learning methods	Autonomous
	Quarry	Present proposal of UAV's usefulness in detecting outcrops of geological rocks	(Blistan et al., 2016)	Rotary wing	Digital Camera Image	Agisoft PhotoScan	Machine learning methods	Autonomous
	Open-pit mine	Classification of rock on the slope using aerial photo-grammetry and machine learning	(Beretta et al., 2019)	Rotary wing	Digital Camera Image	Agisoft PhotoScan	Machine learning methods	Autonomous
	Quarry	Review of the application of field and remote sensing approaches for rock slope characteristics	(Stead et al., 2019)	Rotary wing	Digital Camera Image	Agisoft PhotoScan	Machine learning methods	Autonomous
	Open-pit mine	The article presented the use of UAV and aerial recon-naissance for geotechnical and engineering geological site investigations and data collection on slopes	(Bar et al., 2021)	Rotary wing	digital camera image/	Agisoft PhotoScan	Machine learning	Autonomous
	Quarry	Describe the use of UAV in collecting data for mapping discontinuities within a marble quarry	(Salvini et al., 2017)	Rotary wing	digital camera image	Agisoft PhotoScan	Machine learning methods	Semi-Auton-omous
Landslide	Open-pit mine	Application of UAV-based digital terrestrial photogrammetry to study landslides	(Vrublová et al., 2015)	Fixed wing	Digital Camera Image	Agisoft PhotoScan	Photogrammetry techniques	Autonomous

(Kruzhilko et al., 2023; Kruzhilko et al., 2024). Alvarado et al. (2015) indicated that because only a few sampling sites are used in the air quality monitoring approach, it is not easy to survey the point where blasting has occurred, in real-time. Therefore, they collected dust data during flight by attaching an optoelectrical dust sensor to a small fixed-wing and multi-rotor UAV. The dust monitoring technology shown in this research indicated a technical performance comparable to those of industrial quality dust-monitoring devices. Moreover, the tests described in this paper determined the concentration of particulate matter with aerodynamic diameter less than 10 μm with an accuracy of 1 mg/m3. However, the authors proposed that it is necessary to use other optical sensors and reference calibration with more precise equipment for a more accurate measurement of the concentration (Alvarado et al., 2015)

3.3.2. Rock fragmentation

Using UAV-based photos, Bamford et al. (2016) devised a method for assessing rock fragmentation and conducted laboratory experiments. The research discussed the advantages of using a UAV for aerial rock fragmentation studies in terms of prediction accuracy and time commitment. In order to achieve this purpose, they acquired rock and pile distribution and information using a UAV system and manually taken images of the rocks and piles for comparative analysis. Based on the obtained results, it is admitted that the UAV technology can estimate rock fragmentation within 6% of the accuracy of the existing method, which differs by up to 14% from the actual distribution. Also, UAV-based analysis of rock fragmentation can increase the reliability of measurement and reduce sampling errors without affecting the mining activities (Bamford et al., 2016).

Bamford et al. (2017) also presented the use of a UAV system with artificial lighting to detect rock fragmentation in inadequated lighting conditions, such as those during night work or underground mine work. The components and overall configuration of the aerial vehicle system used for rock fragmentation measurement are illustrated in Figure 5. They analyzed the influence of lighting situations on the determination of aerial rock particles through indoor and outdoor tests. The findings demonstrated that the accuracy of UAV obtained images processing for predicting rock fragmentation is substantially impacted by lighting conditions. Therefore, the assessing precision was improved when artificial lighting was installed on a rock pile or attached to the UAV system (He et al., 2020). Thus, UAVs can perform tasks involving the monitoring or analysis of the working environment and workers in mines when installed with various sensors such as thermal and dust sensors or lights. Table 3 summarizes the four reviewed studies on the application of UAVs to supervise working environments in mine sites. Among the four reviewed research, three studies were implemented in the underground mine with poor lighting conditions, and one case used the dust monitoring system in the open-pit mine.

3.4. Identify Coal fire

The most popular application of UAVs in mining safety management is identifying coal fires. A coal fire is a subsurface occurrence that results in the loss of rich natural resources as well as environmental issues like ground cracks, subsidence and collapse, and atmospheric pollution, which could eventually put human security in danger (He et al., 2020). In addition, underground coal fire has also led to surface subsidence and produced a large number of surface fissures, especially when the burning is severe, thereby prompting geological disasters (Wang et al., 2015). It is challenging

Table 3. Summary of UAV applications for managing the working environment

Purpose	Position	Application	Reference	UAV type	Acquisition Data Image	Software	Data processing	Flight control style
Dust Monitoring	Open-pit mine	Development of a methodology to characterize the blasting plumes in near-real time	(Alvarado et al., 2015)	Both	Dust data	Unknown	Dust concentration value calculation	Semi-autonomous
Rock fragmentation	Underground mine	Suggestions for measuring rock fragmentation using UAVs	(Bamford et al., 2016)	Rotary wing	Digital Camera Image	MATLAB	Calculate the rock size distribution	Autonomous
	Underground mine	Evaluation of applicability of UAV using artificial lighting to monitor rock fragmentation	(Bamford et al., 2017)	Rotary wing	Digital camera image	MATLAB	Machine learning	Autonomous
	Underground mine	Proposal of a drone-based monitoring system that can be used in underground mines	(Raj et al., 2019)	Rotary wing	Digital camera image	PIX4D mapper	Photogmatretry technology	Autonomous

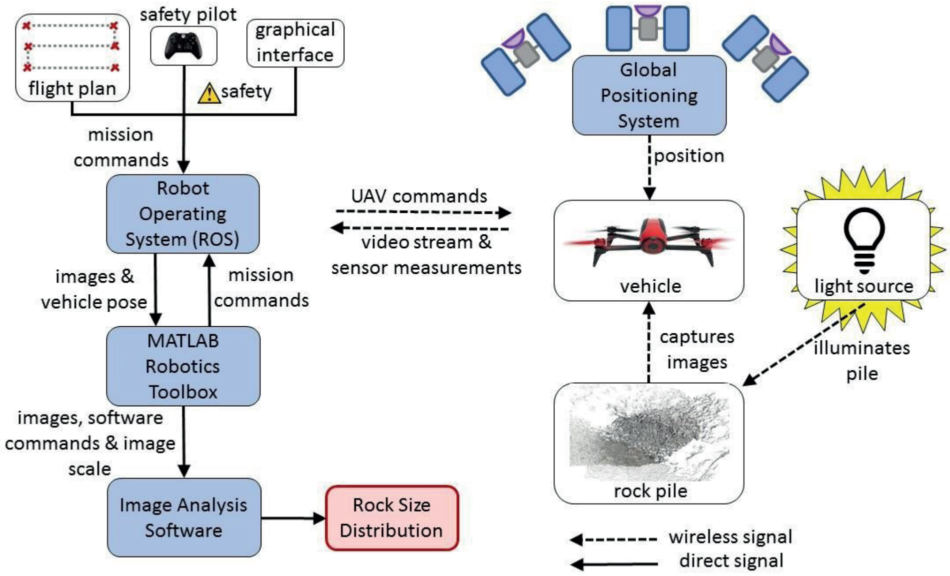

Figure 5. Block diagram of the aerial vehicle system used for aerial fragmentation analysis. Arrows show the typical information flow while conducting a flight plan (Bamford et al., 2017)

to determine the extent of underground coal fires because of some surface parameters, including vegetation, rock, and soil cover over the coal bed (Vice, 2011). For coal fire monitoring, until now, a wide range of technologies have been applied for this point, including index gases, isotopic radon measurement techniques, self-potential methods, magnetic technology, temperature measurements, satellite remote sensing thermal infrared, airborne thermal infrared imaging, and deformation measurement (Yuan et al., 2021). Remote sensing has developed into a practical and helpful technology for the monitoring and detection of coal fires based on anomalies in surface temperature since the early 1960s. However, in contrast to traditional airborne remote sensing, in order to meet the essential demands of spectral, spatial, and temporal resolutions, UAV technology offers fine spatial and greater temporal resolution as well as low cost (Turner et al., 2013). This method allows for a quick and secure assessment of thermal zones, which are frequently located in hazardous and difficult-to-reach terrain. Self-heating coal management is a vital issue to be safe and productive for open-cut coal mining. Inspections are conducted in-situ by trained personnel, or occasionally by manned aircraft thermal imaging surveys. Manual inspection is carried out by visual examination or with the aid of portable thermal cameras, which frequently puts workers in danger. The latter method, using thermal images obtained from manned aircraft, will be performed frequently because it is safer, however this method is high cost and weather dependence. In recent years, Unmanned aircraft systems with lightweight, low-cost thermal imaging cameras have become commercially available and provide an alternative monitoring solution. According to Vasterling et al. (2010) and Sheng et al. (2010), this technology supports a cost-effective solution to carry out sufficiently regular thermal imaging surveys for the management of coal-related ground heating and spontaneous combustion outbreaks (Vasterling et al., 2010; Sheng et al., 2010) and frequently found in difficult or hazardous terrain. Similarly, Malos et al. (2013) proved the potential of UAV in the mining activities to improve the detection, safety, and cost-effectiveness of this novel mode of spontaneous combustion management in open-cut coal mines. Results obtained from the imaging system generate thermal and visible geo-referenced images that can be overlaid onto a digital map of the surveyed area. The data allow rapid detection and accurate localization of anomalous heat levels within target areas that can be updated on the mine plan for management purposes, and thus enables mitigation strategies to be monitored for effectiveness (Malos et al., 2013). A UAV-based thermal infrared (TIR) imaging technique was reported by Li et al. (2018) to safely, timely, and accurately map the characteristics of coal fires which is challenging to implement using conventional technologies. The equipment can solve the problem of the huge workload of data acquisition using handheld thermal infrared cameras. The UAV-born colour images are adopted to establish a cover map and determine the emissivity of ground characteristics. Additionally, TIR images are utilized to calculate the land surface temperature and produce orthophotos, which will then be used to find places where coal fires are present. It has been noted that the accuracy rate of recognized coal fire zones at night reaching a maximum of 92.78% is higher than that during day. The UAV temperature has a strong positive association with the temperature measured by the infrared thermometer for coal fire detection (Li et al., 2018). Besides active mines, it has long been a problem to quickly and accurately locate the burning zones of coal fires in abandoned coal mines all over the world. While Li et al. (2018) proposed a workflow to detect coal fires in the underground mine (Li et al., 2018), Shao et al. (2021) provided a methodology to reconstruct the thermal infrared 3D model of coal fires in the closed mine (Shao et al., 2021). In the Maoergou coal mine, China, they used UAV-based thermal infrared oblique photography to see how coal fires were distributed in terms of burning points. They proposed a 4-step 3D thermal imaging method in which thermal image processing plays the most crucial role. The 3D thermal model vividly depicts the high-temperature zones. The findings show that this approach can be employed as a tool for the depiction of coal fires and other kinds of thermal anomaly scenarios (Shao et al., 2021).

Almost all research used thermal infrared image from UAV to identify the range of coal fires in the coal mine (He et al., 2020; Vasterling et al., 2010), to monitor underground coal fires in the mining area (Wang et al., 2015), analyzes the area changes of LST anomaly (Yuan et al., 2021). In order to estimate the extent of coal fires in the Huojitu coal mine in Shenmu city, He et al. (2020) used a surface survey and thermal infrared remote sensing from UAVs. A digital orthophoto image and a digital surface model of the mining area were generated, with a ground resolution of 3.8 cm. Thereby, the preliminary delineation of the fire regions provides an accurate foundation for the creation of fire control initiatives. The research output demonstrated a low cost and effective technique for locating the primary coal fires in a mine usimg UAV technology and provided a reliable foudation for fire suppression projects (He et al., 2020). Just like He et al. (2020), Yuan et al. (2021) also used infrared and visual images, and Machine learning methods for the study of coal fires in the underground mine. According to Yuan et al. (2021), for coal fire monitoring and extinguishing, accurate acquisition of abnormal land surface temperature (LST) brought on by underground coal fire is crucial. They used UAV thermography to obtain LST images with an extremely high spatial resolution for coal fire monitoring in the coal fire area of Baoan coalfield in Xinjiang province, China. The study uses the related ground measurements to assess the accuracy of UAV LST photos of coal fire zones. According to the findings, the linear regression correlations between UAV LST images and the LST values measured by the thermal imaging cameras and the infrared thermometers are both higher than 0.99. Root Mean Square Error between the thermal imaging camera LST observations and that of UAV is 2.1°C. Furthermore, the study proved that most LST anomalies may be recognized when UAV LST photographs have a resolution better than 7.5 m, and the LST anomaly information loss is minimal (less than 17%). The minimum resolution needed to precisely extract the coal fire zones is 4 meters (Yuan et al., 2021).

Unlike He et al. (2020) and Yuan et al. (2021), Wang et al. (2015) and Vasterling et al. (2010) only utilized thermal images for their mine fire studies. Numerous coal fires burn underneath the coal mines because of indiscriminate mining. Wang et al. (2015) used multi-source remote sensing data in coal fire monitoring in the Majiliang mining area. The thermal field distributions of the study area were captured using Landsat TM/ETM. Detection of a change in thermal distribution determined the locations of the coal fires. Furthermore, based on high-resolution UAV imagery (0.2 m), the texture information, linear characteristics, and brightness of the surface cracks in the coal fire regions were determined. All these data were integrated to create a model for identifying fissures and detecting underground coal fires (Wang et al., 2015). While Wang et al. (2015) processed data by determining a surface temperature field model, Vasterling et al. (2010) used photogrammetry techniquess for this purpose. Utilization of cutting-edge technologies for coal mine fire research, extinction, and monitoring in Northern China, Vasterling et al. (2010) used a UAV equipped with a lightweight camera for thermographic (resolution 160 by 120 pixel, dynamic range -20 to 250°C) and for visual imaging. During predetermined flight missions, the octocopter-shaped UAV can hover at GPS-controlled waypoints. Figure 6 shows photos of coal fires in the Maoergou Open Pit Mine. UAV-based thermal photography instantly offers the spatial distribution of the temperature anomaly with a considerably better resolution than point measurements on the ground. Findings revealed that UAV-born data do well compared to temperatures measured directly on the ground and cover large areas in detail (Vasterling et al., 2010). Findings showed that UAV-derived data outperform ground-based temperature measurements and provide detailed coverage of wide areas.

In short, UAV thermal infrared technology of UAVs is also playing an increasingly critical role in coal fire observing. The scientists applied this method to monitor the land surface temperature in open-pit coal mines, which can reflect the land surface temperature changes in the mining area and the distribution of high-temperature information. Table 4 summarizes the reviewed literature on the application of UAVs for identifying coal fires. Among the seven studies examined, six papers presented the UAV application in

Table 4. Summary of UAV applications for identifying coal fire

Position	Application	Reference	UAV type	Acquisition Data Image	Software	Data processing	Flight control style
Under-ground	Thermal infrared remote sensing from UAV and a surface survey are used to detect the range of coal fires in the Huojitu coal mine in Shenmu city	(He et al., 2020)	Rotary wing	Thermal infrared and visual images	Pix4D mapper	Machine learning methods	Autonomous
Under-ground mine	UAV system and infrared thermal imager were employed to monitor underground coal fires in the Majiliang mining area	(Wang et al., 2015)	Unknown	Thermal image	Unknown	Determining a surface temperature field model	Optional scale
Under-ground mine	Analyzes the area changes of LST anomaly extracted from UAV LST images under different thresholds	(Yuan et al., 2021)	Rotary wing	Infrared and visual images	Unknown	Machine learning methods	Autonomous
Under-ground mine	The results of areal surveys on two coal fires in Xinjiang are presented through UAV born data	(Vasterling et al., 2010)	Both	Thermal Imagery	Unknown	Photogramme-trytechniquess	Autonomous
Open-cut coal mines.	Demonstrating the potential of UAV systems in the mining industry to enhance detection, safety, and economic viability of this unique method of manaing spontaneous combustion in surface coal mines.	(Malos et al., 2013)	Unknown	Thermal image	Unknown	Photogrammetry techniques	autonomous
Under-ground mine	Demonstrate a high-quality workflow for detecting coal fires using retrieved LST by associating UAV TIR imagery with natural colour imagery	(Li et al., 2018)	Rotary wing	RGB colour and thermal imagery	PIX 4D mapper	Photogramme-trytechniquess	Autonomous
Open-pit mine	Discribe a reliable technique for reconstructing the thermal infrared 3D model of coal fires utilizing the UAV thermal infrared oblique photos to identify the distribution of coal fire burning locations	(Shao et al., 2021)	Rotary wing	Thermal infrared image	PIX 4D mapper	Machine learning methods	Autonomous

underground mines, and only one article showed the UAV performance in an open-pit mine.

3.5. Drill and blast operation

Drill and blast design play a significant part in the mine planning and management. Safety and effectiveness are its main effects (Ghose & Joshi, 2012). Blasting is one of the key activities in any excavation system in mining, was dependent on conventional approaches of analysis till new technologies made in-roads in the last few decades (Miranda et al., 2018). Underground mining blasting, rock conditions, and mining techniques all affect worker safety. Because there are many challenges in drilling and blasting in an underground mine, success of a smooth wall blast is depended on drill precision. Production costs and mine safety can be affected by variations in blasting holes. The relief is restricted to the arch and partially down the rib due to the muckpile when the smooth wall holes cannot all be fired on a single delay. Because of this, smooth blasting results will deteriorate further down the excavation line's rib, which could raise safety issues for larger entries (Ghose & Joshi, 2012). The blasting input data can be acquired by the UAV and maintained in digital form, thus UAV images help to benchmark blast success by supports in blast design. In addtion, in order to measure the blast fragmentation, a UAV carrying a video camera is flown above a pile of muck has been blasted. Miranda et al. (2018) used the image analysis software to analyze blast fragmentation photographs in (granite) quarry in Malaysia. Diffirent digital data can be compared with intended blast design with the topography of blasting face and blast design can be adjusted to accomplish desired blasting results. Findings show that blasting information can be viewed seamlessly using various platforms of UAV and results of fragmentation analysis are comparable with actual ones. Thereby, it is possible to create a variable in blast design based on topographic survey and face survey using blasting software (Miranda et al., 2018). Furthermore, the almost real-time rock fragmentation analysis based on a UAV also demonstrates a significant advantage to mining activities,

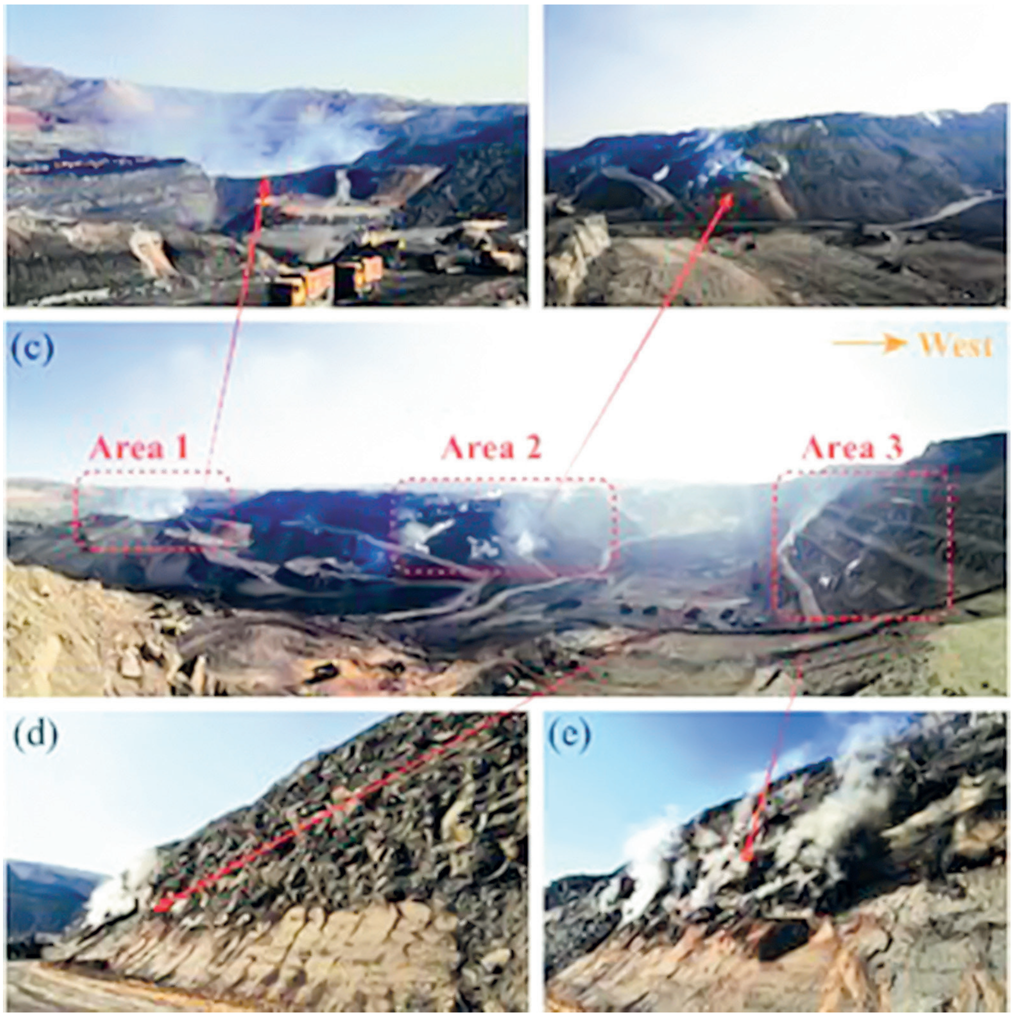

Figure 6. Photos of coal fires in the Maoergou Open Pit Mine (Vasterling et al., 2010)

not only assisting to benchmark blast success but also funishing nessesary particle size profile data to downstream comminution processes to improve the efficiency of these processes. Table 5 summarizes the reviewed literature on UAV applications for monitoring drill and blast operation.

3.6. Application UAV in safety monitoring of mine waste dump

After artificial management is ceased, a recovered opencast coal mine dump is damaged by wind and water erosion from natural processes, leading to land deterioration and even safety incidents. At the Xilinhot open-pit coal mine dump in Inner Mongolia, Xiao et al. (2022) investigated the soil erosion and land decrease after 5 years of such natural processes. UAVs were used to determine the high-precision terrain attributes, the position and the extent of soil erosion, and field sampling was utilized to collect the topsoil's physical parameters. Based on this, the level and spatial distribution of erosion cracks were determined (Xiao et al., 2022). To detect the subsidence of tailings deposited in mines situated in the sub-Arctic, Rauhala et al. employed a UAV technique. The SfM photogrammetry is applied to create an annual topographic model of the tailings' surface,

Table 5. Summary of UAV applications for monitoring drill and blast operation

Position	Application	Refere-nce	UAV type	Acquisition Data Image	Softwa-re	Data processing	Flight control style
Granite quarry	The study employed the UAV flown on blasted muck pile to acquire the video recording of images for measurement of blast fragmentation	(Miranda et al., 2018)	Fixed-wing	Digital Camera Image	Unkno-wn	Machine learning methods	Autonomous

which tracked the change of the surface. Analysis results showed that the monitored displacement of the surface was correlated with an association between erosion, tailings settling, and compression of the peat layer underlying the tailings (Rauhala et al., 2017). According to Gong et al. (2019), dangerous soil erosion issues influenced open-pit coal mine dumps in semi-arid regions of northern China. The typical field investigation approachs are unable to precisely examine gully erosion. Therefore, they employed UAV and Structure from Motion (SfM) technology to capture high-resolution terrain data. At one surface coal mine's dump gully, surveys were conducted both before and after a freeze-thaw cycle. Finally, a 3D digital model of the slope of the drainage field, DEM, and a centimeter-level-resolution digital orthophoto Map were generated. The results indicated that during a cycle of freezing and thawing, there are obvious soil erosion phenomena in the dump's erosion gully. The erosion level was not similar across regions, in which the highest erosion occurred in high-slope regions at the upper edge of the bank (Gong et al., 2019). Besides, dust emission from mine tailings has a significant impact on the surrounding environment of mine zones, which can be mitigated by monitoring and controlling the moisture of mine tailings. In order to create a map of the spatial and temporal variations in moisture content of surface tailings, Zwissler et al. (2017) employed heat sensors placed on UAVs to collect data on iron mine tailings. In order to aid in the management of mine tailings, they also examined the connection between moisture and strength of this material (Zwissler et al., 2017).

In summary, the application of UAVs in research on mine waste dumps has not been much. Current studies mainly focus on the detection of the subsidence, analysis of erosion, and observations of moisture changes on the surface of the mine dump. Table 6 summarizes the reviewed studies on UAV applications for monitoring mine waste management. Among the four reviewed studies, two papers were analyzed the erosion, one paper mentioned potential subsidence, and one presented the moisture changes.

4. Results and Discussion

4.1. Current applications of UAV in mine safety management

After applying the methodology above, 40 research papers and Msc, Ph.D. theses that comprised a wide range of application UAVs within the mine safety were reviewed. Almost all papers from journals were published each one in a different journal. From the review, tendencies that lead to the classification of current UAV applications for the mine safety were found, some statistical information about the application of UAVs in this domain is presented as follows:

(1) Mine surface displacements: 9 papers;
(2) Stability monitoring: 15 papers;
(3) Working environment management: 4 papers;
(4) Coal fire identification: 7 papers;
(5) Drill and blast operation: 1 paper;
(6) Mine waste dump monitoring: 4 papers.

Figure 7 shows the percentage distribution of each UAV application in mining safety and the number of studies classified following that application. The usage of UAVs on mine safety to mines accounted for the majority (40 studies) while only 4 studies related to the mine waste dump. For active and abandoned mines, UAV applications for stability monitoring account for 37.50% of all reviewed studies with

Table 6. Summary of UAV applications for monitoring mine waste management

Application	Reference	UAV type	Acquisition Data Image	Software	Data processing	Flight control style
This paper investigates an outer dump to determine the main factors influencing the degree of soil erosion by UAV based data and field investigation	(Xiao et al., 2022)	Fixed wing	Digital Camera Image	Pix4D mapper	Photogramme-try techniques	Autonom-ous
Monitoring of potential subsidence of tailings	(Rauhala et al., 2017)	Fixed-wing	Digital Camera Image	Agisoft Photoscan	Photogra-mme-try techniques	Autonom-ous
The paper presented a spatial analysis of the erosion gully of the dump performed using the centimeter-resolution DEMs obtained by the UAV.	(Gong et al., 2019)	Rotary wing	Digital camera image	Pix4D mapper	Machine learning	Autonom-ous
The paper presented the method to establish the map of the spatial and temporal changes in moisture content of surface tailings by data of iron mine tailings acquired by UAV	(Zwissler et al., 2017)	Unknown	Thermal image	Unknown	Photogramme-try techniques	Unknown

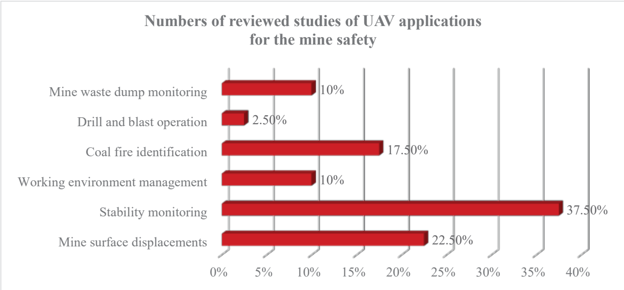

Figure 7. Percentage distribution and number of reviewed studies of UAV applications for the mine safety

15 research. Rock slope was the prevalent application of stability monitoring (9 studies). A coal fire is a subsurface phenomenon that causes not only losses of valuable natural resources but also environmental problems, therefore coal fire identification was the third most frequent application that used UAVs with 7 articles. Notably, it is necessary to capture blasting input data using UAV and maintain it in digital form for safety purposes but there is only one study to mention this issue accounted for 2.50%.

4.2. Types of UAVs used in mine safety management

From the literature review, UAVs can be categorized into three main types: fixed-wing, rotary-wing, and both for various applications in mine safety management. Table 7 illustrates the number of studies that used three types of UAVs for each purpose. Among the 40 studies, two with unknown types of UAVs used were excluded. The fixed-wing UAV requires a particular take-off distance because it cannot take off or land vertically, which presents a challenge for small-area missions like mining operations. Furthermore, the fixed-wing UAV has a small payload and is susceptible to wind speed during take-off and landing. Nowadays, fixed-wing UAVs like Sensefly eBee and Skywalker are widely used in mining areas (Fig. 8) (Ren et al., 2019). The rotary-wing was the prevalent type of UAV for applications of mine safety because rotary-wing UAVs can hover, take off, and land vertically.

Table 7. Numbers of reviewed studies by UAV types used for each purpose of the safety and risk management

Type	Rotary Wing	Fixed Wing	Both	Un-known	Sum
Determining mine surface displacements	2	4		3	**9**
Stability monitoring	9	3	1	2	**15**
Working environment	3		1		**4**
Identify coal fire identification	4		1	2	**7**
Drill and blast operation		1			**1**
Mine waste dump monitoring	1	2		1	**4**
Sum	**19**	**10**	**3**	**8**	**40**

4.3. Types of data acquired by sensors for UAV application in mine safety management

From 40 reviewed literature papers, three types of data acquired by sensors were found for UAV applications in mine safety management as shown in Table 8. The highest use was of images or videos acquired by RGB cameras (visible image) (34 times), followed by thermal infrared images or data (8 times), and environmental monitoring data (data acquired by dust sensor mounted on UAV) (1 time). The total of the acquired data shown in Table 8 is not 40 because two types of data were captured for UAV application reported in three publications (He et al., 2020; Yuan et al., 2021; Li et al., 2018). The visible images can easily analyze the size, height, coordinates, width of a fracture, rock mass, or rock fall while a thermal infrared images can detect temperature and density. The images or videos captured by digital cameras were mainly used for stability monitoring including the vertical and horizontal land subsidence, and the use of thermal infrared image/ data was relatively frequent in identifying coal fires.

(a) Sensefly eBee (b) Skywalker X5 (c) Drone AscTec Falcon 8 (d) DJ Phantom 4

Figure 8. UAV platforms are widely used in mine safety (Ren et al., 2019)

4.4. Software and UAV Data Processing in mine safety management

With the use of specialized sensors, UAVs can acquire information for various features of objects related to mine safety such as topography surface, temperature, humidity, dust, rock fragmentation, etc. However, there is still no standardized workflow or well-established techniques to follow for analyzing, processing, and visualizing the information captured.

Table 8. Numbers of reviewed studies classified by acquired data types by sensors mounted on UAVs for each purpose of the mine safety management

Purpose	Digital camera	Thermal infrared image or data	Environ-mental monitoring data	Sum
Determining mine surface displacements	9			**9**
Stability monitoring	15			**15**
Working environment	3		1	**4**
Identify coal fire identification		7		**7**
Drill and blast operation	1			**1**
Mine waste dump monitoring	3	1		**4**
Sum	**31**	**8**	**1**	**40**

Among 40 reviewed studies, the UAV data processing method could be identified from these studies including Photogrammetry techniques, Machine learning methods, and other indices calculation methods as shown in Table 9. Machine learning techniques are often applied in the management of mine safety to exploit the information from the large amount of data acquired by the UAVs. This method is able to estimate some parameters regarding the displacement, slope stability, rock fragmentation size, or change of land surface temperature anomaly in the study area. Machine learning was the prevalent method for application involving stability monitoring (18 studies). The photogrammetry technique is used mainly in determining mine surface displacements. Rock mass rating, dust concentration value, and rock size distribution are the most popular indices for assessing slope stability, characterizing the blasting plumes, and measuring rock fragmentation. However, the use of these indices was observed to be insignificant for four studies related to stability monitoring, working environment, and coal fire identification.

Because data processing may be time-consuming, several software tools and techniques have been developed to enable faster data processing. From the literature review, the five

Table 9. Numbers of reviewed studies classified by UAV data processing method

Purpose	Photo-gram-metry technique	Machine learning method	Others	Un-known	Sum
Determining mine surface displacements	7	2			**9**
Stability monitoring	3	10	1	1	**15**
Working environment	1	1	2		**4**
Identify coal fire identification	3	3	1		**7**
Drill and blast operation		1			**1**
Mine waste dump monitoring	3	1			**4**
Sum	**17**	**18**	**4**	**1**	**40**

software used to process the UAV-based data for various applications in mine safety activities, namely Pix4Dmapper, Agisoft Metashape, Visual SfM, MATLAB, and 3D survey. The most commonly adopted software solutions in the works reviewed to support and accelerate the data analysis procedure are summarized in Table 10. Among the 40 studies, nine with unknown software were excluded. Overall, the highest use was of Agisoft Photoscan software (17 times), followed by Pix4Dmapper (9 times), MATLAB (2 times), 3D survey (2 times), and Visual SfM (one time). Agisoft Photoscan and Pix4Dmapper can exploit for the construction of 3D models and orthomosaics. However, the former was the prevalent software for stability monitoring and the latter was the most commonly used tool for determining mine surface displacements and identifying coal fire. MATLAB is applied mainly for the mine safety activities involving the working environment.

Table 10. Features that can be monitored with UAVs

Purpose	Pix 4D	Agi-soft	Visual SfM	MAT-LAB	3D survey	Un-known	Sum
Determining mine surface displacements	3	3			2	1	**9**
Stability monitoring		13	1			1	**15**
Working environment	1			2		1	**4**
Identify coal fire identification	3					4	**7**
Drill and blast operation						1	**1**
Mine waste dump monitoring	2	1				1	**4**
Sum	**9**	**17**	**1**	**2**	**2**	**9**	**40**

4.5. Styles of Flight control used for UAV application in mine safety management

The 40 reviewed literature papers were grouped into three types according to the styles of flight control as manual, autonomous, or semi-autonomous. In other studies, the style was not reported. Table 11 shows three styles of flying control used for UAV applications in all works to ensure mine safety management. Autonomous flight was the most commonly used for purposes (29 papers) while semi-autonomous flight was performed in three studies. A manual style of operation was only mentioned in one paper that presents UAV applications in the monitoring of ground subsidence.

Table 11. Numbers of reviewed literature papers on the flying control style of UAVs

Purpose	Manual	Autono-mous	Semi-Autono-mous	Un-known	Sum
Determining mine surface displacements	1	6		2	**9**
Stability monitoring		10	2	3	**15**
Working environment		3	1		**4**
Identify coal fire identification		6		1	**7**
Drill and blast operation		1			**1**
Mine waste dump monitoring		3		1	**4**
Sum	**1**	**29**	**3**	**7**	**40**

5. Conclusions

The usage of the UAV cannot solve all the problems related to the mining industry but it can help some specific issues in mine safety. This paper introduces research results from applications using the more advanced UAV platforms and sensors in the monitoring of mine safety. The results showed that UAV is a common tool in surface mining, underground mining, abandoned mining, and mine waste dumps. It is an efficient and low-cost approach compared to the traditional monitoring methods. This paper only reviewed some of the research conducted in the past 12 years for using UAVs technology in mine safety. These reviews found that current applications of UAVs in mine safety can be categorized into six types including mine surface displacement, stability monitoring, working environment, coal fire identification, drill and blast operation, and mine waste dump management.

Among the current applications, stability monitoring in open-pit mines and the opencast quarry has been applied the most. Moreover, this application also prefers to use rotary-wing UAVs. The most popular software and data processing techniques for UAV applications in mine safety were Agisoft Photoscan and the Machine learning method, respectively. Regarding the styles of flight control, and autonomous control style was more prevalent for most applications of mine safety. Notably, the most popular kind of data captured by sensors on UAV applications in mine safety management was images or videos acquired by digital cameras. However, this type of camera was replaced by a thermal infrared camera when studying coal mine fires.

At present, the application of UAVs in mine safety management is going through a period of rapid development because of their high time efficiency, high mobility, and low cost. Selecting suitable UAVs and sensors according to the actual target requirements is a critical issue in mine monitoring studies as well as in mine safety research. However, in order to obtain better application results, it is necessary to combine UAV data and other kinds of data such as satellite remote sensing data, surface monitoring data, and downhole data.

Conflicts of interest

The authors declare no conflict of interest.

Acknowledgments

Thanks to two anonymous reviewers and editorial comment for their valuable comments in the earlier version which helped us to improve the quality of the manuscript.

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