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Applications of UAVs in mine industry: A scoping review

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Abstract

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Keywords

UAV, unmanned aerial vehicles, mine industry, drones, application of UAV

RESEARCH ARTICLE

Applications of UAVs in mine industry: A scoping review

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Abstract

In recent years, a variety of technologies have improved mining operations. One of them is the Unmanned Aerial Vehicles (UAVs), the emerging technology that has been changing the mining process, boosting mining safety and productivity. The main purpose of this paper is to review the applications of UAVs in the mining industry based on the results of 113 research papers over the past twelve years, from 2010 to May 2022. The potential applications of UAVs in the mining industry are broad. Based on the paper identified, eight categories are used to classify UAV applications in the mining sector. The reviewed literature revealed that UAVs are an excellent tool for multitasking at any stage of a mining project and in any type of mine. The findings of this study may serve as some guidelines for developing the necessary requirements for the use of UAV technology in mine sites.

Keywords: UAV, unmanned aerial vehicles, mine industry, Drones, application of UAV

1. Introduction

UAVs, also referred to as drones, are used primarily for military operations where the hazard criteria of sending a human-piloted aircraft would pose too much risk or the circumstance makes using a crewed aircraft impossible [1]. Remote control or autonomous flight are both options for these aircrafts. According to Dastgheibifard and Asnafi [2], there is no unique word to name an unmanned aircraft. Apart from Unmanned Aerial Vehicle, commonly they also are referred to as UAS (Unmanned Aerial System), UAV (Unmanned Aerial Vehicle), RPAS (Remotely Piloted Aircraft System), RPA (Remotely Piloted Aircraft), UCAV (Unmanned Combat Aerial Vehicle), and Remote Controlled (RC) Helicopter [2]. In this paper, UAVs and drones will both be used.

In recent years, the UAV is available for a variety of applications and can be used for disaster management [3], habitat destruction assessment [4], crop monitoring [5], vegetation mapping [6], search and rescue missions [7], mining process [8], infrastructure management [9], etc. Besides, UAV technology is broadly applied in a variety of fields. According to the modern demand for autonomous technology in several fields of agriculture, military, and civilian usage, Nawaz et al. (2019) have investigated a variety of UAV applications [10]. Singhal et al. (2018) highlighted the evolution and development of UAVs in civil and military applications [11]. Potential applications of UAVs for the construction industry and agriculture can be found in the study of Dastgheibifard and Asnafi (2018) [2] and the research of Kim et al. (2019) [12], respectively. In addition to the use of drones in the military section and for commercial purposes, UAVs have been applied as an innovative technology in the mining industry. Rathore and Kumar (2015) revealed the potentiality of UAVs in the mining sector and its implications for mining's future. In the mining process, UAVs have a great prospect to minimize manual efforts in data acquiring, surveying, mapping, safety monitoring, machinery tracking, infrastructure monitoring, etc. [1].

UAVs are an ideal technology for the mining process as they have access to areas that are dangerous and unreachable to employees. Compared to traditional procedures, these methods offer better characteristics in terms of time, precision, safety, and prices [13]. There are many studies

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reviewing the applications of UAVs in the mining industry. While Park and Choi (2020) contributed to the categorization of existing UAV applications in the mining process from exploration to reclamation [14], Shahmoradi et al. (2020) published a thorough analysis of the usage of UAV technology in the mining sector [15]. Additionally, Ren et al. (2019) considered the existing scientific study using UAVs in the mining area to assess the applications in environment, reclamation, and mining [8]. Meanwhile, Lee and Choi (2016) reviewed the trend of the UAV technology and its usage at mining sites. Most of these studies have identified applications of UAVs in the mining industry, but some have not been systematic, and others have not fully exploited the applications, especially the mine safety issues and applications in abandoned mines have not been highlighted. The objective of this study is to review the applications of UAVs in the mining industry in all types of mines, including open-pit, underground, and closed mines.

2. Material and methodology

2.1. Search criteria

This study applied the systematic literature review method to detect, assess, and interpret all studies relevant to the applications of UAVs in the mining sector. The objectives of the study were set as targets and disintegrated into individual concepts and related keywords. In order to find high-impact publications concerning the application of UAV in the mining process, many titles and keywords are selected from conferences and prestigious journal around the world. Currently, thousands of scientific articles can be found and accessed from online databases. This study used data from some important sources, including Google Scholar, Web of Science, IEEE, Science Direct, etc. Between January 2010 and July 2022, the databases were searched for the terms "drone" OR "unmanned aircraft system/UAS" OR "unmanned aerial vehicle/UAV" OR "remotely piloted aircraft systems/RPAS" OR "remotely piloted vehicles/RPV" AND "mine" OR "mining industry" OR "mining process" OR "mining operations/activities" OR "mine sites/areas". A list of the search syntaxes utilized for the study retrieval is summarized in Table 1.

Table 1. The search syntaxes.

Drone related terms	Mine related terms
Unmanned Aerial System (UAS)	Mine
Unmanned Aerial Vehicles (UAV)	Mining industry
Drone	Mining process
Remotely Piloted Vehicles (RPV)	Mining operations/activities
Remotely Piloted Aircraft Systems (RPAS)	Mining areas/sites
Application UAV/UAS/Drones	Mine sites/areas

2.2. Study identification and selection

A systematic attempt was made to collect and compile all relevant internet documents. The retrieved data were screened and vetted based on their relevance to the particular applications of UAVs in the mining process. In addition, the collected literature was assessed on relevance in terms of publication type and time. These criteria were identified to confirm that only journal papers, conference articles, and book chapters published in English in the period 2010–2022 were included. Other kinds of publications were excluded, including editorial notes, commentaries, and unpublished manuscripts. After deleting duplicates, screening is performed based on titles and abstracts to check eligibility criteria. The full text of the manuscripts was then accessed for inclusion in the review. There are 16,225 articles found based on keywords listed in Table 1. A total of 16,000 papers were excluded because of titles, abstracts, and duplicate removal screening. The remaining 225 publications were assessed for suitability on each application. As a result, only 113 full-text papers that met the aforementioned criteria were collected for review.

3. Applications of UAVs in the mining industry

Drones technology can be applied in the mining process in so many various ways. In this paper, we demonstrated that there are eight main applications of UAV in the mining industry at the moment. This section gives a thorough introduction to UAVs and the most significant applications in the mining industry.

3.1. Application UAV in surveying mine

One of the applications in the mining industry is surveying. It is mostly used for mine planning, calculation of mineral resources and ore reserves, and reconciliation [16]. The creation of 3D models of mine sites and the use of UAVs for surveying have both become increasingly important. UAV technology can obtain high-resolution images, which are then transformed into 3D surface models such as digital elevation model (DEM), digital surface model (DSM), and digital terrain model (DTM), and can be used for producing topographic maps, calculating excavation volume, showing the mine site in 3D forms.

3.1.1. Application UAV in terrain surveying in surface mines

3.1.1.1. Construction of surfaces and evaluation of their accuracy. When compared to conventional approaches in terms of cost and efficiency, drones seemed to offer substantial advantages in the surface generations. This technology has been extensively used in the construction of surfaces and their accuracy assessment. The literature review indicates that some studies presented the results of building DEM for open-pit mines using UAVs [17,18]. Cho et al. [17] have verified the applicability of UAV technology to mining engineering. As a result, an orthophoto and DEM model are generated by the Agisoft Photoscan software and UAV images with 10 cm resolution. Similarly, Nghia [19] assessed if it would be possible to create 3D models of deep open-pit mines using UAV image data. The findings showed that the 3D model established from UAV data met the accuracy requirements for creating the mine terrain map at a 1:1000 scale.

Topographic information is indispensable data for some purposes in the mining process. The generated DSM can be utilized to evaluate the status of the mining process and to estimate ore carrying capacity [20]. Moreover, in the study of Gil and Frąckiewicz, a spatial query and assessment of the surface mine were conducted utilizing the Quantum GIS tool and DEM data [21]. Xiang et al. [22] selected an open-pit mine in Beijing, China, as the research site to evaluate geomorphic variations using a DEM generated using high-resolution UAV images and SfM photogrammetry.

Besides, some scientists have used other traditional methods to check the accuracy of DSM obtained using UAVs [23] or analyzing the precision of the DEM derived from photogrammetric processing [24–27]. Additionally, others assessed the performance of this technology in 3D modeling applications [28–31]. Forlani et al. (2018) demonstrated that the accuracy of photogrammetrically-created DSMs bases on geometric and physical factors, such as the camera network design, the accuracy and distribution of ground control points (GCPs), image scale, stereo base-length to object distance ratio, ground sampling density (GSD), camera network geometry, camera calibration, point cloud noise, base-length to object distance ratio, percentages of strip overlap, image processing, image matching, and outlier removal algorithms [32]. Similarly, Nguyen et al. [26] believed that the accuracy of UAV-derived DSMs is influenced by topographical factors in the active surface mines, such as slope, relative elevation, and number of GCPs. Determination of the number of GCPs to ensure the accuracy of mapping and minimize measurements in the field can be found in Nguyen (2021) [24,33]. Drones have also been employed to verify the quality of a DSM in mines [34,35]. The results revealed that the DSM model has great accuracy [35]. While Tien Bui et al. [35] found that the use of UAV and SfM in difficult topography areas (such as open-pit mine areas) is still poorly understood, Chirico and DeWitt [25] indicated that DSMs can be created with a high level of accuracy and relative precision thanks to UAV imagery and SfM photogrammetric techniques.

3.1.1.2. Creating 3D models and evaluating their accuracy. 3D models are necessary tools for experts in the mining industry because they provide high-quality representations of mining sites. In recent years, UAV photographic measurement technology has been crucial in the development of 3D modeling in mine areas. Applications for the UAV-based 3D models include everything from civil engineering to managing natural resources. Several studies have been conducted in recent years to assess the performance of UAVs in 3D modeling applications. Worthy reviews of such publications can be found in [36–38]. Utilizing a rotary-wing UAV to conduct 3D modeling in an open-pit limestone mine was presented by Kang et al. (2018) [39]. The application of UAVs has been demonstrated as a substitute tool for establishing a 3D map of open-pit mines by Bui et al. (2019). Large-scale 3D topographic maps were successfully modeled depending on the UAV photographs [40]. Similarly, in applying UAVs in building 3D models for large surface mines, Battulwar et al. [29] developed a practical setup to utilize affordable drones to create 3D models and high-resolution photos for large surface mines. According to Vassena and Clerici [31], 3D-colored models of large surface mines can be generated using a terrestrial laser scanner (TLS) with images combined with UAV-based digital photogrammetry. Similar to Vassena and Clerici, Tong et al. [30] analyzed and combined point cloud data produced by TLS with UAV photos and created a 3D model for monitoring and mapping surface mine sites with decimeter-level accuracy. In addition to utilizing software such as Agisoft, Pix4D, etc., to establish 3D models, integration of UAV data into the GIS environment is a great method for making 3D models. Filipova et al. [41] carried out a spatial analysis to create a 3D model of an open-pit quarry by integrating UAV data into GIS software. Besides, Tscharf et al. [42] used UAV images, terrestrial images, and inside views of an object to better 3D models by joint image processing to make detailed, accurate, and complete reconstructions. Regarding the UAV's application in generating 3D models, Ulusoy et al. [43] have used a lightweight UAV to acquire digital aerial images of an open-pit mine for the ultimate purpose of 3D modeling the terrain. The studied results were a DEM with a high resolution of 0.3 m/pixel and an orthorectified aerial image with a very high resolution of 0.04 m/pixel. Also, to produce a highly accurate DSM, Le Van et al. [44] used a post-processed kinematic drone to acquire images in open-pit mines to demonstrate that drones can be used for an open-pit mine topographic survey. The generation of precise 3D modeling in the grave-pit mine also is presented in the study of Shahbazi et al. [38]. They assisted that UAV-based images have the prospect for providing data with a very high spatial and temporal resolution for 3D modeling.

In addition to demonstrating the potential of creating 3D models, the accuracy of a UAV-based 3D model was mentioned in a lot of research. While Park et al. [36] compared the precision of traditional field survey methods with UAV-generated 3D models of coal stockpiles, Wang et al. compared the absolute coordinates between the UAV point cloud and the GCPs to assess the precision of 3D geometry from low-elevation UAV photos at the Zijin Mine in China [37]. González-Aguilera et al. [27] indicated that although the UAV-based modeling methodology necessitated using various steps consecutively to capture a real-based 3D model, and therefore error propagation is necessary, the degree of obtained precision is sufficient.

3.1.1.3. Mapping and terrain surveying. According to Leo Stalin and Gnanaprakasam [45], a mine map can give information to optimize mining activity. Thus, mapping is a very indispensable aspect of the mining industry. At present, UAV technology has been used broadly in mining areas for terrain surveying. Drones can acquire high-resolution photos, which can then be converted into 3D surface models to establish topographic maps. Based on this approach, Leo Stalin and Gnanaprakasam [45] used Quadrotor UAV to obtain nadir and oblique aerial images. The digital orthophotograph and 3D models created from these data were used to construct the mine map. In a similar way, Salvini et al. [46] used UAVs to create 3D discrete fracture network models after mapping fractures in a marble quarry. Katuruza and Birch [47] applied UAV technology to map opencast highwalls in surface mines at Isibonelo Colliery of South Africa to create data for updating geological models and provide the latest information for planning mines to enhance short-term plans. Using nadir and oblique aerial pictures taken by a UAV, Rossi et al. [48] proposed a method to rebuild the quarry topography in Bari, Italy, and then carried out a feasibility analysis. In relation to mapping and surveying in mine sites, the type of drones used in the mine topographic survey can be found in [17,49]. While Lee and Choi [49] used a rotary-wing UAV (DJI Phantom2 Vision+) to carry out the topographic survey at small-scale surface mines, Lee and Choi [17] presented a description of topographic surveying method employing a fixed-wing UAV (SenseFly eBee) at open-pit mines.

3.1.2. Application UAV in terrain surveying in underground mines

There are risks to both worker safety and mining operations when mining activities in deep and high-stress conditions are undertaken. Because of their small size and manoeuvring ability, UAVs have numerous potential applications in underground mining. In this section, we only review the studies on UAV applications for surveying and mapping underground mines. Li et al. [15] demonstrated the use of UAV in mapping underground mine and suggested a 3D tunnel system search and mapping algorithm. Additionally, a study by Ge et al. [50] presented the use of UAV data to map the underground mine in New South Wales, Australia. Russell et al. [51] concentrated their research on the application of UAVs as measurement tools for collecting data to model and map rock masses inaccessible in underground mines. Papachristos et al. [52] proposed a combined method for drone-based autonomous navigation and mapping in underground mines. Besides, thermal images always are useful data for studies in underground mines. An interesting example of using UAV thermal imagery in an underground mine to create a 3D model can be found in the study of Turner et al. [53]. Similarly, Turner et al. [54] also proved that both thermal and multispectral imaging were successful in generating georeferenced 3D point clouds and meshes and mapping discontinuities.

3.1.3. Application of UAVs in terrain surveying of abandoned mines

Monitoring and mapping closed mines play an essential role in reducing the environment's dangers. However, it is challenging to survey large regions using traditional, time-consuming, labor-intensive, expensive monitoring techniques. As a more costeffective approach, UAV technology may be an alternative [15]. It cannot be denied that UAV technology plays an important role in surveying abandoned mine areas with high accuracy. In a study [55], a digital georeferenced orthoimage and DTM with a 5 cm resolution could be acquired by coordinates of pre-installed ground control points (GCPs). Verification based on the GCP positions found that the created DTM had an error of about 14 cm, which was deemed acceptable for use in closed mine subsidence mapping. Besides, in order to address the issues of low efficiency, high cost, and high labor intensity in conventional manual field mine surveys in the closed quarries in Baitu, Suzhou City, Dai and Xu [56] used UAV technology to create 3D model and calculate earthwork. Currently, reclaiming land from abandoned open-pit mines is a crucial environmental responsibility [57]. Thus, identifying the amount of soil for the preparation of the investment's expenditure plans is needed. Also related to earthwork calculation, Molnar and Domozi [57] generated a 3D surface model based on photogrammetry and UAV images. As a result, the amount of filling material needed for the recultivation of an abandoned mine was determined by 3D models.

Motyka [58] used photogrammetry to map anthropogenic terrain alterations on abandoned coal mines in Katowice for land reclamation. Obtained results revealed that, in difficult geometric conditions requiring constant alterations in the UAV flight altitude, it is essential to utilize a parallel spatial orientation system, such as on-board inertial sensors and GPS. Topography changes connected to anthropogenic and meteorological influences rapidly and precisely were also detected in the study of Yucel and Turan [59]. They created 3D terrain models of the mine lakes using high-resolution images from a UAV. 3D modeling of UAV photos was performed with the Agisoft software using the most popular SfM technique.

In addition, UAV can be considered a potential instrument for high-spatial-resolution mapping. Therefore, the radiologically contaminated land regions can be identified, and the level of contamination and its isotopic nature in many long-disused mining sites can be detected and quantified quickly [60]. According to Neumann et al. [61], methane emission is reduced but does not stop entirely when a coal mine does not work. Therefore, to minimize the dangers associated with working in nearby operational underground mines using a 3D point cloud generated by optical sensors, the authors produced a 3D virtual mine map to determine the quantity of gas that can be stored in closed mines based on micro-drone.

3.2. Drilling & blasting (before & after drilling or blasting)

One of the essential steps in open pit mining is drilling and blasting, which is necessary to reduce the size of in-situ rock blocks to rock fragments that can be handled by mining machinery [62]. In many early-stage mining projects, these activities represent the crucial, complex, safety-critical and necessary parts. However, in the open pit mines, the current methods used to monitor the blasting procedure are carried out by hand, manually, infrequently, and these techniques may put technical manpower in dangerous conditions. Thus, UAV systems were used in various studies to monitor and enhance the blasting process in open pit mines. There were three stages of blasting for the UAV-based monitoring including before, during, and after. A high-speed camera was mounted on the UAV to observe the blasting process. It was used to evaluate the blast initiation, sequencing, misfired holes, and stemmed ejection. Bamford et al. (2020) used the gathered aerial data to produce orthophotos and 3D point cloud models for assessment in the before- and after-blast phases. Accordingly, the volume expansion and broken rock pile can be estimated [63]. Medinac et al. (2018) presented the findings of a case study in a surface mine where a UAV was utilized for mapping the pit walls before the blasting. The post-blast rock fragment size distribution was also calculated using data obtained by the UAV [62]. For many mining operations, measuring post-blast rock fragmentation is crucial since the efficiency of all downstream mining and comminution processes is impacted by the distribution of rock sizes created during the blasting process [64]. Bamford et al. (2017) presented the use of UAV technology to carry out real-time rock fragmentation studies at a laboratory scale. In this study, the design of a UAV system that acquires information on rock fragmentation in real time has been thoroughly explained [65]. Similarly, Bamford et al. (2016) proposed a method to determine rock fragment measurements using UAV-based images on the laboratory scale. The results showed that rock fragmentation can be estimated within 6% of the accuracy of the current approach, which can vary up to 14% from the real distribution [66]. Furthermore, UAVs are considered to be great tools for identifying rock fragmentation in poor lighting conditions, as in the study of Bamford et al. (2017). They described the parts and overall configuration of the UAV system used to measure the number of rock fragments during nighttime or underground mine operations. The results concluded that the accuracy is increased if artificial illumination was added to a pile of rocks or installed on the UAVs [67].

In addition to determining the rock fragment size distribution, volume expansion, and broken rock pile, the UAV system is utilized to identify the exact locations of the drill holes. In the study of Valencia et al. (2019), a specially programmed UAV acquired photos of the drilled blasting location, which were then processed by photogrammetry software to generate an orthomosaic map and DEM of the area. The models are analyzed to determine the as-built positions of the drill holes. Therefore, in order to obtain the most uniform distribution of explosive energy in the rock mass, an optimization model is used to manage the quantity and configuration of the charges in each drill hole [68]. Blasting frequently takes place near population centers and frequently results in the release of particulate substances and gases that could be harmful to human health. Thus, it is necessary to monitor air quality in mining areas after blasting. Alvarado et al. (2015) suggested using small UAVs equipped with air quality sensors to accurately characterize blasting plumes in close to real-time. In this study, high-resolution instantaneous micrometeorological data are generated from flight instrument data received as telemetry from the UAV that can be used to help interpret the concentrations discovered by the on-board air quality sensors [69].

3.3. Mine safety and risk management

UAVs can be effectively used to prevent unnecessary accidents by detecting dangerous hazards and identifying new sources of danger. The literature reviews showed that UAVs are applied in mining areas for safety purposes, including mine surface displacements, stability monitoring, working environment, coal fire identification, drill and blast, and mine waste dump operations.

3.3.1. Mine surface displacement

3.3.1.1. Monitoring of ground subsidence in mining areas. The primary risk factor for the destruction of buildings and other structures, which eventually results in surface collapse and environmental harm, is surface subsidence caused by coal mining. Thus, during coal mining, it is essential to identify deformation [70]. Detection and measurement of ground subsidence are implemented in all types of mines, but the use of UAVs for monitoring subsidence is mostly done in underground mines. However, according to Yavuz (2019), the determination and detection of deformations that can create in surface mines play an important role in terms of safety and maintenance of production [71]. While Yavuz (2019) have been used a UAV to observe deformations after open pit mining activities [71], Suh and Choi (2017) established a sinkhole subsidence map caused by dangerous mining in an abandoned mine [55]. Determination of the terrain vertical deformations induced by underground mining using UAVs can also be identified in [72–75]. Dawei et al. (2020) insisted that the UAV technology can detect the surface dynamic subsidence basin of coal mining regions in a short period, and then reliable parameters of mining subsidence were found [72]. Similarly, Ignjatović Stupar et al. (2020) presented the method for the large mine subsidence monitoring in the Wangjiata coal mine in Inner Mongolia of China to obtain factors of mining subsidence in the short term [73]. Also, Pal et al. (2020) analyzed the 3D point cloud created from the UAV images to determine the surface subsidence. Accordingly, the estimation of subsidence from the perspectives of geometry and volume loss was given based on the prognosis model [74]. The accuracy of monitoring the terrain subsidence measurement by UAV was also mentioned in many studies. Ge et al. (2016) generated a subsidence map of an underground mine in New South Wales, Australia. In this paper, there are three various methods to detect mine subsidence, including UAV technology, total station, and laser imaging detection and ranging (LIDAR) measurements. Obtained findings revealed corelative accuracy between three ways, but the first way, with high-resolution photos acquired by UAV and analyzed by DSM, was much more efficient and faster [50]. Also related to testing the precision of using AUV in monitoring mine subsidence, Jóźków et al. (2021) compared the results of investigating the terrain vertical deformations of the mining areas by UAV and the findings calculated using LIDAR data. The analysis results identified that the UAVs can obtain data with less noise and more accurate values of the terrain subsidence than the UAV LiDAR sensors. Moreover, the conducted experiments found that UAV photogrammetry enables to detect of medium-scale deformations, but it is necessary to perform the investigations in non-vegetated areas, and it should not be made UAV flights to collect data during the growing season in order to keep the best quality [75].

3.3.1.2. Monitoring of horizontal displacements caused by mining. In addition to using UAVs in monitoring terrain vertical deformations, this tool can be used to identify horizontal displacements. At present, analyses of UAV-based images for observing horizontal variations induced by underground mining are very rare. Although these displacements always do not exceed values of a few decimeters, observing these measurements to evaluate and reduce their disadvantageous influences is needed. Thus, using UAV-induced ultra-high-resolution orthomosaics, Puniach et al. (2021) introduced a method to automatically calculate the vector field of horizontal displacements influenced by underground mining. The findings revealed that the accuracy usually does not exceed the size of two pixels and depends on the image resolution [76]. Moreover, UAVs can be used in monitoring land surface displacements, as the study by Ćwiąkała et al. (2020) [77]. In this research relying on points of observation lines created in the field, horizontal displacements are calculated for monitoring purposes. In addition, there are also several kinds of periodic deformations that have been discovered and shown their development throughout time. To calculate the ground displacements, the acquired findings are compared [77].

3.3.1.3. Documentation of landslides. Currently, there is not much research on landslides caused by mining. Vrublová et al. (2015) applied UAV technology to document the landslides and unreachable areas of the Nástup Tušimice mine in the North Bohemian Brown Coal Basin. Thereby, an orthophoto and 3-D model of the landslide areas were generated based on UAV images. Accordingly, an appropriate measurement method can be discovered for the operation of landslides and hard-to-reach areas of the mines [78]. Liu et al. (2022) investigated the Songmugou Landslide by exploiting UAV and small baseline subset interferometric synthetic aperture radar (SBAS-InSAR). Then, based on integrating geological, structural and rainfall data, they assessed the displacement features, activity zones and secondary landslide risks in the research region [79].

3.3.2. Stability monitoring

3.3.2.1. Slope stability monitoring. UAVs are also frequently used to provide the best result in determining stability, such as slope stability and rock slope. Because the slope's stability is directly connected with the safe operation of the surface mine and the safety of personnel, a slope stability assessment can help decrease damage caused by this situation [80]. Ge et al. (2016) assessed the potential of UAV technology for monitoring the highwall slope stability in [50]. UAV-derived surface models such as DEM [81], 3D models [82,83], and DTM [84] can be used to determine the stability of the mine slope. In addition to using the UAV images, McLeod et al. (2013) assessed the slope stability using a 3-D point cloud created from video images taken with an UAV and Structure from Motion (SfM) photogrammetry software. Besides the photogrammetry techniques, Vemulapalli and Mesapam (2021) used the machine learning method in analyzing slope stability to evaluate mine hazards. From UAV-derived DEM, the slope stability parameters can be determined. These were fed as input data for the Artificial Neural Network (ANN) model.

In addition to assessing slope stability for open pit mines, UAVs are an excellent, reliable instrument for determining the slope stability of quarries. Buill et al. (2016) presented the results of the process of unstable slope monitoring and damage assessment after the events, as well as control of infrastructure influenced by photographic images or 4K video captured from UAV platforms [84]. Similarly, the application of UAVs in mapping for quarry surveying and slope evaluation was described in the research by Nagendran and Ismail (2018). Agisoft Photoscan software was applied to produce the orthophoto, DSM, 3D dense point cloud, and 3D model. Accordingly, the primary discontinuity sets for rock slope stability studies can be identified via facet extraction [83].

3.3.2.2. Rock slope stability analysis. Many studies have analyzed the rock slope stability. Most of the research was done in active mines except for the study by Salvini et al. (2018), which was performed in a closed mine [85]. In this study, high-resolution data of a blocky rock mass inside a quarry that is prone to discontinuity-controlled instability processes was obtained by UAV. The UAV-derived 3-D model of the region enabled precise detection and geometric measurement of the geological discontinuities that separate significant amounts of rock [85]. Stead et al. (2017) assess the use of remote sensing methods for the features of rock slopes. At the same time, they indicated the importance of these methods in the assessment of rock slope stability [86]. According to Anua et al. (2020), the mechanics of instability often rely on the nature, strength, and structures of the rock mass. They thus used the UAV technology to detect the structure of rock mass and assess the stability of the collected quarry surface [87]. Similarly, Hartwig and Moreira (2021) used the high spatial resolution images of UAVs for structural evaluation and as a georeferenced base-map and kinematic slope stability assessment in the Itaoca district (Southeastern

Brazil). The results revealed that UAV images are useful in determining the structural characterization of rock masses as they can categorize different fracturing levels and explore structural regions in the whole slope face [88]. Also related to rock classification to evaluate rock slope, Beretta et al. (2019) rebuilt the topography through UAV aerial photogrammetry, and then rocks on the slopes were divided into four types, including vegetation, granite, diorite, and soil. Using the machine learning method to process data, the obtained results showed the impact of the change on any kind of visual identity of lithological materials [89]. According to Viana et al. (2019), natural rock masses showed different geological hazards. Therefore, the generation of 3D models of the quarry wall for the stability analysis of the rock slope is needed. In the study [90], they presented a method to create the 3D model of the Jardim Garcia quarry using Agisoft Photoscan software and UAV imagery. Blistan et al. also demonstrate the great capabilities of UAVs in detecting geological rock outcrops, notably those in inapproachable areas of mines [91]. Salvini et al. (2017) also utilized UAV-derived 3D point clouds to reconstruct the quarry terrain. Discontinuities were then mapped deterministically in great detail [46]. In addition, it should be noted that ground failure on slopes of natural rocks is a geological risk with potentially fatal consequences for employees in the mining industry. For this reason, Bar et al. (2021) used UAVs to create a preliminary geotechnical model to analyze slope stability to assist in the management of risks associated with geological hazards [92].

3.3.3. Coal fire identification

Detecting coal fires is the most common use of UAVs in mining safety management. Nearly all studies utilized UAV-based thermal infrared images to detect the range of coal fires in the coal mines [93,94], keep track of underground coal fires in mining areas [95] and assess the area variations of LST anomaly [96]. Some research combined UAV images and machine learning techniques to determine coal fire zones [93,96,97]. He et al. (2020) conducted a surface survey and used thermal infrared remote sensing from UAVs to estimate the size of coal fires in the Huojitu coal mine in Shenmu city. Based on a digital orthophoto image and a DSM of the mining sites created by UAV data, the fire regions were delineated preliminarily. As He et al. (2020) did, Yuan et al. (2021) used infrared and visual photos with an extremely high spatial resolution and machine learning method to investigate coal fires in an underground mine in Xinjiang province, China. The study evaluated the accuracy of UAV LST photographs of coal fire regions using relevant ground measurements. The findings revealed that it is necessary to use images with a minimum resolution of 4 m to precisely extract the coal fire zones [96]. While He et al. (2020) [93] and Yuan et al. (2021) [96] integrated the machine learning method and UAV images to study coal fires in underground mines, Shao et al. (2021) applied that method for reconstructing the thermal infrared 3D model of coal fire areas in a surface mine, China. They used UAV-based thermal infrared oblique photos to identify coal fires and delineate the high-temperature zones in detail [97]. The potential of UAVs to improve the detection of spontaneous combustion in surface coal mines has been demonstrated in a study by Malos et al. (2013). The data allow for the quick identification and precise localization of abnormal heat levels inside target zones, which may then be updated on the mine plan for management purposes, enabling monitoring mitigation techniques' efficacy [98]. In addition to using UAV thermal images, Wang et al. (2015) have combined UAV-based photos and multi-source remote sensing data to monitor coal fires in the Majiliang mining area. Using Landsat TM/ETM, the thermal field distributions of the research area were recorded. Additionally, the textural data, linear features, and illumination of the surface cracks in the coal fire zones were identified using high-resolution UAV images (0.2 m) [95]. While Wang et al. (2015) analyzed data by generating a surface temperature field model, Vasterling et al. (2010) employed photogrammetry techniques for this aim. A UAV fitted with a lightweight camera was utilized by Vasterling et al. (2010) for both thermographic and visual imaging. UAV-based thermal photography rapidly supplied the spatial distribution of the temperature anomaly with a considerably better resolution than point observations on the ground. Thus, UAV-derived data outperform ground-based temperature measurements and provide detailed coverage of large areas [94]. In addition, Li et al. (2018) proposed a UAV-based thermal infrared imaging technology to establish the map of the characteristics of coal fires safely, promptly, and correctly, which is difficult to implement with traditional technology. The color photos captured by UAVs are used to create a cover map and assess the emissivity of ground features. 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 [99].

3.3.4. Erosion detection

Because it is challenging to replant the technology produced by mining waste and the slopes are usually steep, one of the biggest problems affecting recovered areas in the extractive industry is the erosion process. Therefore, Carabassa et al. (2021) proposed a method to calculate soil losses caused by water erosion in mine-restored sites using UAVs and GIS. They concluded that the high spatial resolution of drone photos allowed for thorough observation of erosive processes, receiving information from vast and difficult-to-reach slopes that are typically impossible to measure with traditional methods and generally upgrading the mine restoration monitoring procedure [100]. Similarly, Padro et al. (2022) demonstrated that remote sensing employing UAV-based images is a highly helpful method for the morphometric assessment of topographies in surface mining operations, particularly for erosion processes associated with recovered regions. They described a technique for determining water erosion processes using UAV photography in working quarries without access to pre-existing images or mapping for comparison [101]. Besides using UAVs and GIS, combining UAVs with machine learning is a great approach to finding and examining indicators of rill erosion on the slopes of the tailings dam slopes. Kim et al. (2022) presented rill erosion analysis through image processing and UAV data. In this study, Convolutional Neural Network is selected as the main algorithm, and the UAV-acquired images were prepared with an image editor software and Matlab to generate labeled images and masks for model training [102].

3.4. Haul road optimization

Surface mines typically have operational issues, including puddling and improper water flow along haul roads. These situations lengthen truck cycle times, enable the material on haul-road to deteriorate quickly, decrease production because of downtime, and necessitate more frequent road maintenance. UAV technology allows capturing georeferenced pictures of a place from numerous perspectives. Therefore, Benevenuti and Peroni (2021) have demonstrated that using a high-resolution UAV-derived DEM is an efficient method for quickly and accurately identifying anomalies. Thus, haul-road conditions can be identified after rainfall, or the potential occurrence of such anomalies can be predicted before they cause more damage [103]. Besides, an improvement in haul road conditions can have a significant effect on mine operations, such as increasing safety, productivity, tire life, and lowering maintenance costs. Medinac et al. (2020) implemented UAV technology on an important portion of the haul road at Bald Mountain Mine to demonstrate the possibilities of haul road monitoring. The findings showed that orthophotos and DEM can be utilized to evaluate the state of the road's smoothness and verify the conformance of the road plan [104]. Also, it can not be denied that mine haul roads deteriorate quickly as a result of excessively large loads on inferior construction materials. Douglas (2021) described thoroughly the application of optical photogrammetry from UAV and vehicle vibration response modeling to detect the mine road defects. In this study, the authors used four detection methods, and UAVs were shown to be the best option for quantifying the condition of a broad area road network, including surface roughness, faults, and grade irregularities, to maximize bad condition rehabilitation and lower total road expenses [105].

3.5. Regular monitoring of tailing dams

In addition to the applications of UAVs in mine operations mentioned above, such as mapping, mine safety, blasting, and drilling, etc., UAVs are also useful tools in research on mine waste dumps. Over a 3-year period, Rauhala et al. (2017) conducted to monitor an impoundment of tailings and determine the possibility of tailings subsidence using UAVs. The study utilized SfM photogrammetry to create annual topographical simulations of the tailings surface, which made it possible to track how much the surface had moved over time. The results showed that tailings impoundment monitoring with UAVs is precise enough to support management activities for impoundments and track surface displacements in the decimeters [106].

3.6. Environmental monitoring

3.6.1. Land damage assessment and ecological environment monitoring

Mining operations have a positive economic impact but also seriously harm the environment's ecosystem and the land. Therefore, assessing environmental damage and continuously monitoring the ecological environment are crucial parts of land protection and serve as the foundation for choosing various management strategies in the later stages following the mining operations [8]. According to Ren et al. (2019), UAV technology is a quick and safe way to acquire data, thus, it has proven to have significant potential in monitoring the land and ecology. UAVs employing a variety of sensors have achieved good results in a variety of applications, such as the characterization of marshes impacted by underground coal mining [107] and the extent of damage in land influenced by subsidence [108]. Moreover, the natural topography and groundwater level have been significantly affected by mining subsidence, which leads to grain security in the area being threatened. Thus, it is essential to calculate the damaged farmland regions in the coal-grain overlap areas (CGOA). Ren et al. (2020) presented a low-expense, quick, and non-destructive approach for assessing land damage in a typical CGOA in eastern China based on maize aboveground biomass, which was calculated utilizing an UAV. The key findings from the survey displayed that underground coal mining induced serious ecological issues, including subsidence and destruction of vegetation [109].

Surface coal mining not only has a great influence on the mines but also affects the waste dumps. After artificial management is discontinued, a recovered opencast coal mine waste is influenced by natural processes such as wind and water erosion, which can lead to land deterioration and even safety incidents. Xiao et al. (2021) investigated soil erosion and land damage after five years of natural processes at the Xilinhot surface coal mine dump in Inner Mongolia using UAVs and field sampling. Based on this, it can identify the extent and spatial distribution of erosion breaks [110].

3.6.2. Monitoring of air, soil and water pollution

Fang et al. (2019) proposed a method employing regression analysis and hyperspectral photos taken with a UAV to map the amount of stored Iron in the soil of a mining area in Hevei Province, China. The UAV-derived hue saturation intensity (HSI) images were preprocessed through GPU-based Python script. Afterwards, they added it to the PhotoScan platform. Besides, the study selected the partial least squares (PLSR) model, which was the most appropriate for estimating Iron concentrations [111].

In the Sokolov lignite district of the Czech Republic, Jackisch et al. [94] used a small drone system to study pyrite and the products of its subsequent weathering in mining waste of replanted tailings regions. Using a UAV-created DEM, hyperspectral information was analyzed and adjusted for illumination, topographic, and atmospheric impacts. It was feasible to confirm the existence of goethite and jarosite in the study region by classifying the hyperspectral photo data [112].

According to Park and Choi (2020) [14] using UAV to monitor pit lakes can decrease the dangers involved in water sampling, lower costs related to sampling, and raise data collection frequency. Hence, Castendyk et al. (2019) to chose the sample depth of the mine pit lake using a drone. Prior to taking a water sample, a drone is used to measure the field's temperature and specific conductance, which are used to determine the best sampling depth. The findings show that utilizing UAVs to observe pit lakes can provide managers with vital information regarding pit lakes' behavior and water quality [113].

In addition to aerial photograph function, the UAV is capable of implementing a variety of duties when equipped with lights, communication modules, and thermal and dust sensors [14], such as dust monitoring, rock fragmentation analysis, etc. Alvarado et al. (2015) obtained dust data during flight by installing an opto-electric dust sensor on a tiny UAV. The results showed that using this method can be determined the concentration of particulate matter with an aerodynamic diameter of fewer than 10 μm with an accuracy of 1 mg/m^3. However, to measure concentration more accurately, it is essential to use other optical sensors and calibrate a reference with a more accurate instrument [69]. Besides, one of the main causes of global warming, acid rain, air pollutants, and smog is underground coal fires which begin naturally or as a consequence of people's activities. A few years ago, UAVs mounted with gas sensors showed success in the control of pollution and remote monitoring. Dunnington and Nakagawa (2017) detected rapid and secure gas from an underground coal fire by UAV flyover. Data on gas concentrations gathered by drones offer a secure option for determining the level of a burning coal seam [114].

3.6.3. Land reclamation and ecological restoration assessment

Although surface mining is still an obligatory activity, it may become unsustainable if deteriorated sites aren't restored [115]. Thus, it is necessary to monitor the restoration after extractive operations. In the case of ecological restoration monitoring, it was noted that the vegetation distribution can be understood via UAV-derived images such as multispectral photos, aerial images, or near-infrared photographs [20]. Lee et al. (2016) applied UAV-acquired imagery to study and identify changes in the ecological rehabilitation region of surface limestone mines in Gangwon-do, Korea. Through comparisons with orthophoto and DEMs created using the UAV-based photogrammetry, modifications in the ecological restoration area were monitored [116]. Urban et al. (2018) employed UAV technology to collect data on a spoil heap in regions with different vegetation denseness during the leaf-off phase in a post-mining site of Czech Republic. In addition, to detect random mistakes in the data captured by the UAV system, they examined the impact of the plant coating and chose distinctive plant regions, such as a bush, forest, shrub, and grassland. In grassy areas, a comparison of the individual data showed that the medium displacement ranged from 0.01 to 0.08 m, and the precision of the difference was about 0.03 m [117]. To characterize post-mining areas and detect vegetation structure, Moudry et al. (2019) assessed the value of point clouds produced by UAV photogrammetry and LiDAR. They took airborne images both with and without leaves in the Most basin, Czech Republic. As a result, in the leaf-off condition, the point cloud's point density was greater than in the leaf-on condition. The findings showed that it may be possible to determine plant structure features for researching a vulnerability to slope failure or evaluating the success of restoration projects using the association of UAV images from leaf-off and leaf-on phases [118]. Also related to mine restoration after mining, Padró et al. (2019) proposed a cheap, practical method to observe surface mine rehabilitation through UAV photos. They utilized a small UAV attached to a multispectral sensor to measure the field spectroradiometer. Using the obtained spectral data and land cover categorization, exposed soil, mine waste dumping and other extensions of the land cover were all identified and quantified. The findings indicated that UAV photography can give quantitative data regarding rehabilitation failures or success in terms of observing the regions that have vegetation, mining waste dumping, or bare soil at various stages of restoration [115]. According to Johansen et al. (2018), UAVs are the perfect tool for collecting data on vegetation cover and changes in land use since they can repeatedly capture higher-resolution photographs at a low height. Thus, they used UAVs to evaluate the effectiveness of surface coal mine rehabilitation at three distinct mine sites in Australia. The authors gathered multi-temporal UAV imagery in a variety of mine rehabilitation sites covering a range of rehabilitation kinds, ages, and land uses. Then, they utilized these data sets to create maps of land covers, landforms, and vegetation types as indicators of the effectiveness of rehabilitation [119].

3.7. Application of UAV in search and rescue actions

The potential use of a UAV in rescue operations in an underground mine has been demonstrated in many studies. Zimroz et al. (2021) described an automatic signal processing method to recognize a particular sound in the presence of significant, time-changing noise from UAVs. Accordingly, a missing or hurt person who asks for assistance but is unable to move or use any communication device can be detected [120]. In addition, using UAVs to detect victims during the mining process, this technology can also be utilized to search for the locations of buried objects caused by these activities. In the study of Stoll and Moritz (2013), a fluxgate magnetometer has been mounted on a UAV to measure near-surface geophysics observations. The obtained results demonstrated the capability of magnetometer to identify metallic things buried in the ground. As a result, the position of electrical railroad machineries and a large number of family homes damaged by landslides in surface coal mines were successfully detected [121]. In addition, based on an aerial magnetic sensor mounted on the UAV helicopter, Eck and Imbach (2011) created a detailed magnetic map and determined different ferrous objects in the soil. They used magnetic scanning to detect buried infrastructure objects and vehicles [122]. The use of UAV technology for search has been creasing in recent years. According to Malehmir et al. (2017), however, there are many difficulties, including the UAV's electromagnetic noise, short flying times, and restrained load capacity, geophysical surveys conducted by UAVs are appealing for the investigation of land minerals. Thus, based on flight flexibility and robustness, they evaluated the prospect of rotary-wing UAV systems to identify the iron-oxide deposits in central Sweden [123].

3.8. Application UAV in surveying mine geology

The UAV has no complex operation and fewer limitations on the environment. Furthermore, it is capable of taking part in some high-hazard activities; in particular, it can assess and gauge some challenging geological environments. Recent studies highlight the prospect of UAVs in geology. Jakob et al. (2016) and Jakob et al. (2017) proposed a new approach for processing UAV-based hyperspectral data and assessed whether it could be used in geological surveys. The experiments indicated that geometrical and radiative adjustment offers noteworthy outcomes even in regions with little lighting and steep topography. Additionally, it has been demonstrated that geological applications are suitable for adjusted hyperspectral mosaics [124,125]. Meng et al. (2022) mentioned applications of UAV system in mine environmental geology and offered new concepts and solutions for the management of geological environments [126]. Beretta et al. (2019) described the method to classify the lithology of surface mines in Cajati, Brazil, automatically by small UAVs and machine learning techniques. UAV-captured images were utilized to categorize materials in accordance with observational geological characteristics [127]. The same purpose as Beretta et al. (2019), Kirsch et al. (2018) carried out a comprehensive field geological survey and gathered ground-based SfM photogrammetric and hyperspectral datasets as well as UAV-based datasets. Based on the analysis of these datasets, two main lithological areas were successfully identified. On the other hand, the kinds of rocks dominated by quartz and plagioclase were also distinguished using the hyperspectral data [128]. In order to support geological field campaigns, Heinke et al. (2019) developed multi-sensor drones for obtaining magnetic and hyperspectral data in Finland. The UAV multi-sensor system was used for collecting data to generate DSMs that depict mean sea level altitudes of the relative surfaces of objects. As a result, a geological map of the study area can be established [129]. Also associated with the determination of geological characteristics, Jackisch et al. (2019) presented integrated information obtained and analyzed from drone multi-sensor investigations incorporating magnetic and optical remote sensing data [130].

4. Discussion

4.1. Strength of the study

To the author's understanding, this article is the most complete review of UAV applications in the mining industry. Although some existing review publications used a structured approach to the literature review, most have not specifically discussed all applications of UAVs in the interest area, which could lead to the omission of relevant research papers. In this review, the mentioned papers were published between 2010 and May 2022, as shown in Fig. 1.

There was only one study published in the first five years of the decade (except for 2013). The number of publications has gradually increased from 2015 with nine studies to nearly 20 studies in the years 2019, 2020, and 2021. In the recent four years (January 2019 to May 2022), around 57 of the 113 papers have been released, showing that there has been a surge in interest in UAV applications in the mining industry starting in 2019. Besides, the number of publications has significantly increased

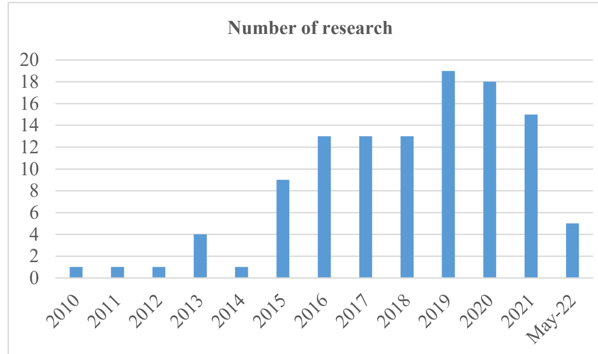

Fig. 1. The number of research from January 2010 to May 2022.

in recent years, indicating a major rise in knowledge, awareness, and interest in the use of UAVs in the mining industry.

The obtained results revealed that the applications of UAVs in mining activities was considered by many nations in the world, as illustrated in Fig. 2. A total of 113 papers were reviewed, with the majority performed in China (18/113), United States ranked second with 9 studies, and followed by Vietnam with 8 studies, Canada and Australia, each has 7 studies, Poland, Brazil, Spain, Czech Republic, and Italy, each country has 6 studies. Some other countries have only 1 to 5 studies, such as Korea (5 studies), Slovakia and Turkey (4 studies each), India and Finland (3 studies each), Sweden, Mexico, and Switzerland (2 studies each), Bulgaria, Hungary, England, Chile, Malaysia, Mongolia, and Germany (1 research each). This can be accounted for by the fact that mining is prioritized in these nations, in particular in China.

Furthermore, the majority of findings also showed that the drones' technological capabilities and innovation are motivated by computers, software, and machine learning algorithm such as linear regression, logistic regression, random forest, etc., which enhanced the performance of the UAVs. Although it is not currently possible to conduct a systematic evaluation of applications due to the shortage of experimental research in the hazardous environments of underground mines, quarries, toxic gas leak areas at coal mines, lack of standardization of UAV operations in the hazardous areas, and lack of knowledge as well as awareness, this paper follows a structured methodology that includes eight applications of UAVs, in which, based on each application, it can be divided by space such as open-pit mine, underground mine, closed mine or divided by nature of work, and type of work. This study reviewed 113 research articles and MSC/Ph.D. theses that covered a variety of UAV applications in

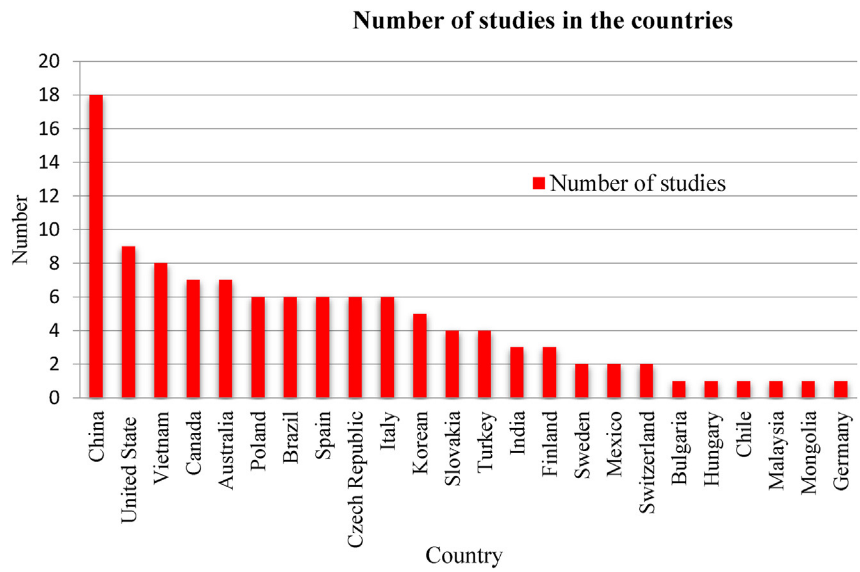

Fig. 2. The distribution of the number of studies in countries.

the mining industry. As a result of the review, it was determined that certain trends helped categorize current UAV uses in the mining process, as can be seen in Table 2 and Fig. 3.

The most popular application of UAVs in the mining industry, as recorded in the literature, is surveying mines, with a total of 44 studies (39%). This application can be performed in three types of mines but mostly open pit mines. The majority of research concentrated on the construction of surfaces and evaluation of their accuracy (18 studies), creating 3D models and evaluating their accuracy (9

Table 2. Applications of UAVs in mining industry.

No.	Application	Number
1	**Application of UAVs in surveying mine**	44
In surface mines		
	Construction of surfaces and evaluation of their accuracy	18
	Creating 3D models and evaluating their accuracy	9
	Mapping and terrain surveying	5
In underground mines		
	Terrain surveying	5
In abandoned mines		
	Terrain surveying	7
2	**Application of UAVs in drilling & blasting operations**	7
3	**Application of UAVs in mine safety and risk management**	
Mine surface displacement		
	Monitoring of ground subsidence in mining areas	7
	Monitoring of horizontal displacements caused by mining	2
	Documentation of landslides	2
Stability monitoring		
	Slope stability monitoring	5
	Rock slope stability analysis	8
Coal fire identification		
	Monitor coal fires in the mining area	7
Erosion detection		
	Determining water erosion processes	3
4	**Application of UAVs for haul road optimisation**	3
5	**Application of UAVs for regular monitoring of tailing dams**	1
6	**Application of UAVs in environmental monitoring**	
	Land damage assessment and ecological environment monitoring	4
	Monitoring of air, soil and water pollution	4
	Land reclamation and ecological restoration assessment	5
7	**Application of UAVs in search and rescue actions**	4
8	**Application of UAV in surveying mine geology**	7

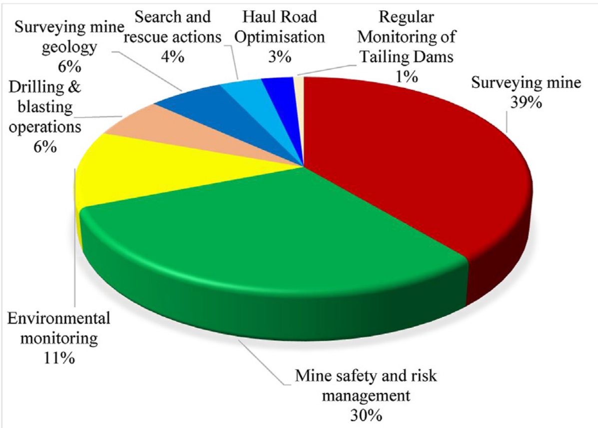

Fig. 3. Applications of UAVs in the mining industry.

studies), mapping and terrain surveying (5 studies), terrain surveying in underground mines (5 studies), terrain surveying in closed mines (7 studies). The second highest contribution, at 30%, was used for mine safety and risk management, such as mine surface displacement (11 studies), stability monitoring (13 studies), coal fire identification (7 studies), and erosion detection (3 studies). Thirdly, with a total of 13 research, is environmental monitoring. These studies were evenly distributed to applications related to land damage assessment and ecological environment monitoring, monitoring of air, soil, and water pollution, and land reclamation and ecological restoration assessment. 6% of papers addressed the drilling & blasting operations, and the same number applied to survey mine geology. Application UAV in search and rescue actions and haul road optimization accounted for 4% and 3% of publications, respectively. Only 1% of the papers mentioned monitoring of tailing dams, when the use of UAVs occurs mostly in the research on mine waste dumps.

4.2. Knowledge gaps

This review confirms the continued interest of the scientific community in the applications of UAVs in mining activities. The literature revealed that there are many key advantages of UAVs application in mining operations, such as low cost, lightweight and convenience for moving from one location to another, can fly at various altitudes, can access difficult-to-reach places, and taking pictures in high definition and making videos [1]. Therefore, UAV technology can replace the traditional approach and quickly perform formerly labor-intensive and time-consuming activities, collecting periodical data with significantly higher resolution than satellite images [8]. In addition to all the benefits of UAVs, there are some shortcomings and challenges that prevented UAVs from being used more frequently in the mining industry that must be solved for future development. According to Rathore and Kumar [1], some difficulties that should be mention are the establishment of high-quality reference data, software and maintenance concerns, short flight duration, collision risk, limited payload like laser scanners, and safety and security issues.

Moreover, the restrictions of the UAVs specification, such as battery life, can be significant difficulties. Like some other fields, energy consumption when performing tasks in the mining sector can also face many challenges due to the power limitations of UAVs. UAVs use batteries to power their hovering, wireless connections, data transmission, and image processing. Thus, to save energy, a choice must be taken on whether real-time onboard data and image analysis or offline processing should be used [13,131]. At the same time, because of low endurance, unmanned aerial vehicles (UAVs) must fly more often to cover a big area, which is difficult in areas with limited access to electricity. Therefore, UAV users must be prepared, well-trained, and proficient in operating drones, especially in difficult terrain conditions with a shortage of light, such as in underground mines, with many toxic gases such as closed mines that have been banned for a long time, or in search and rescue activities when there is an accident caused by mining. Absolutely, quicker processing times and more precise data may be acquired quickly.

It is not denied that flying UAVs face several challenges in harsh underground conditions. It is challenging for an operator to fly UAVs in underground mines because these activities perform in confined areas, with restricted visibility, dense concentration of dust, the absence of wireless connection systems, and inadequate illumination. According to Shahmoradi et al. (2020), in order to tackle these obstacles, the developed UAVs must, at the very least, be able to fly in an environment without any external lighting and navigate completely autonomously without the use of GPS. Besides, this device should be designed to be able to recognize and avoid obstacles when flying indoors. Additionally, the UAV must be able to operate in dangerous underground mine conditions with lots of dust and smoke as well as high humidity and change pressure. Therefore, Shahmoradi et al. (2020) recommended that UAVs must be designed to be shockproof, waterproof, dustproof, and resistant to variations in pressure, temperature, and humidity over the entire mine. Besides, they also suggested that the environmental challenges in underground mine sites may be overcome by using encased drones [15].

Moreover, the environment, especially the weather and light, plays an important role in conducting data collection and their quality in mine areas. Currently, some UAVs have a too low payload, which makes them susceptible to environmental factors such as weather and terrain [60]. Weather conditions might harm UAVs and make them unable to complete their missions; even flights may be delayed. Although the weather is not a factor affecting data gathering in underground mines, this condition provides a challenge in surface mines by causing deviations from UAV's predesignated paths [13,132]. In order to solve this problem, scientists are urged to undertake their studies in poor weather conditions. Waterproofing electronic components as well as wind deflectors or wind preventers, may be used, especially in rainy situations.

Apart from these challenges, the local rules and regulations are other big limitations. These vary from one nation to another, however, it is necessary to obtain the appropriate permission from the relevant authorities in order to follow the rules [1]. One issue that needs to be underlined is the existence of forbidden regions when UAVs cannot be used. Creating UAV routes through no-fly areas is an important field of research. Therefore, it is necessary to plan the regulations to facilitate and secure the deployment of data collection in those prohibited areas.

5. Conclusion

In this paper, the author presented an in-depth analysis of the UAV applications in the mining industry which have outstanding use and potential. The paper demonstrated a rise in the number of publications on this topic over the past years. The obtained results indicated that UAV technology with the intelligent flight management system and data processing techniques is incredibly promising in various applications of the mine industry. Currently, modern technology is largely known in many countries, including developed as well as developing nations, and this technology is becoming more mature in over the world. The review has shown that UAVs are a great tool to conduct mining-related activities in surface, underground, and closed mines in all 3 phases: pre-mining, during mining, and post-mining. In this article, 113 publications were reviewed, categorized, and several gaps were found, allowing recommendations for further study. As demonstrated in the paper, there are still a lot of restrictions and difficulties in the early research and development stages. Some limitations were discussed in-depth such as UAVs specification (battery life), hash working environment (underground mine), weather and light conditions, and the local rules and regulations. Accordingly, methods to address these challenges have been proposed. UAVs will be used in the mining sector more frequently if these drawbacks are resolved.

Ethical statement

The authors state that the research was conducted according to ethical standards.

Funding body

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Conflicts of interest

The authors declare no conflict of interest.

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